

Vega spacecraft encounters with comet Halley

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The spacecraft Vega 1 and Vega 2 encountered comet Halley on 6 and 9 March 1986. Their scientific payload comprised 14 instruments, which collected data concerning the comet's optical characteristics, dust emission, and neutral gas, plasma and electromagnetic field environment. The main features of the encounters are described and highlights of the first scientific results are presented.

THE Vega 1 and Vega 2 missions had two main scientific goals: studies of Venus by means of balloons and landers, and fly-by studies of comet Halley. The basic design of the spacecraft chosen for this mission is the same as has been used many times to deliver Soviet landers and orbiters to Venus. In June 1985, these spacecraft successfully delivered the first balloons into the Venus atmosphere (each carrying 4 scientific experiments), as well as delivering landers with 9 experiments to the surface of the planet. The results of this part of the mission are published elsewhere¹⁻³. The fly-by modules made a gravitational manoeuvre near Venus, and finally Vega 1 and Vega 2 encountered comet Halley on 6 and 9 March 1986.

The most important aim of these encounters was to take a first look at a cometary nucleus, not as a star-like object, but as a spatially resolved body. The encounters allowed us to evaluate the comet's size, shape and reflectivity, and to observe complicated processes in the inner part of the gas and dust coma.

Successful imaging of the comet from the spacecraft required a steerable platform which could be automatically pointed with great accuracy at the cometary nucleus. The most difficult problem was to locate the nucleus, with its very low albedo, against

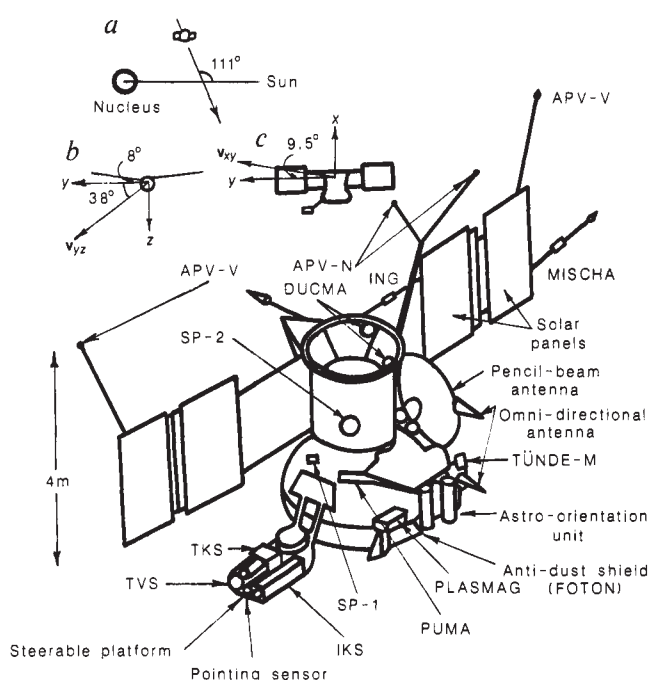


Fig. 1 The Halley probe of the Vega spacecraft (Vega 1 and Vega 2 were identical), showing the locations of scientific instruments. The insets show the spacecraft trajectory relative to the Sun-nucleus direction (a) and the orientation of the spacecraft axes (x, y, z) relative to the spacecraft velocity vector (v), in top (b) and side (c) views.

the background of the very bright coma with gas and dust jets. The accurate pointing achieved allowed the examination of the innermost parts of the coma and near-nuclear region by means of television cameras and infrared and optical spectrometers placed on the steerable platform.

Mission and encounter

The Vega project was an international one. Although the spacecraft themselves were controlled by the Soviet Union, the sci-

entific programme and payload were coordinated by the International Science and Technical Committee (CIST), representing scientific institutions from nine countries. The CIST designed the Vega mission to be complementary to the European Giotto and Japanese Suisei cometary missions.

Figure 1 is a schematic illustration of one of the (identical) Vega spacecraft, showing the locations of the various scientific instruments (see Table 1), and the orientation of the spacecraft velocity relative to the comet. The weight of the craft is ~2,500 kg (without the Venus module, which added another 2,000 kg).

The fly-by speed was extremely high (~78 km s⁻¹), because the sense of orbital motion of the comet is opposite to that of the Earth, and thus of the spacecraft. This high speed resulted in a strong dust hazard and required dust protection of parts of the spacecraft^{4,5}.

Table 1 Parameters of the Vega mission flights

	Vega 1	Vega 2
Launch	15 December 1984	21 December 1984
Venus fly-by, descent probe landing, balloon insertion into the Venus atmosphere	11 June 1985	15 June 1985
Passage through the comet Halley coma	7:20:06*, 6 March 1986	7:20:00*, 9 March 1986
Nearest distance to the nucleus (km)	8,890	8,030
Encounter velocity (km s ⁻¹)	79.2	76.8
Distance of the encounter point from the Sun (AU)	0.7923	0.8341

* Time of closest approach to the comet nucleus (UT).

Table 2 presents some important parameters and Fig. 2 shows the trajectory of the Vega flights. Most of the data were sent to



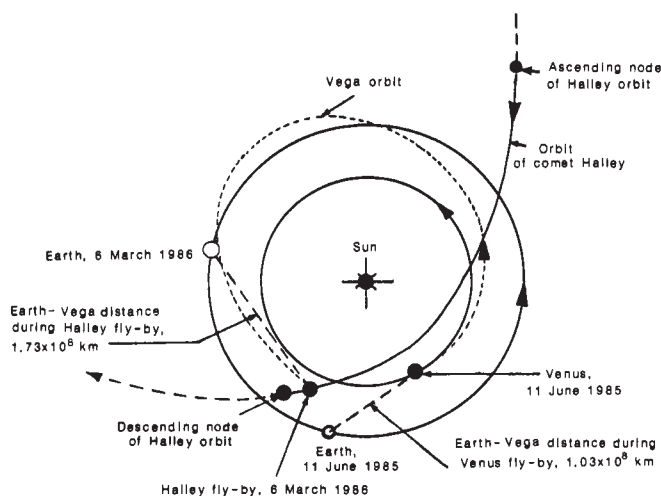


Fig. 2 The orbits of the Earth, Venus, comet and spacecraft. The Vega 1 and Vega 2 orbits are nearly identical.

Earth in real time (at a transmission rate of $65,536 \text{ bit s}^{-1}$), because of the dust hazard during the encounter. Table 2 lists the scientific instruments carried by the spacecraft.

The flight operation centre was located in Evpatoria (Crimea), but most investigators were in Moscow at the Space Research Institute, where they were able to obtain all data in real time. Deep-space antennae in Evpatoria (main mirror 70 m) and Medvezhy Ozer, (64-m mirror), near Moscow, received the telemetry. The encounter sequence of measurements began 2 hours before the predicted time of closest approach. The plasma science instruments started their measurements 2 days before the encounter, but used a low-bit-rate telemetry system with tape-recording until the last hours of the encounter.

Although there were some instrument failures caused by dust particle impacts, all the Vega experiments were successful. The solar-battery current decreased by almost 50% after the encounter, but the Vega spacecraft are still functional, and could be used to study another target. The possibility of extending the Vega mission is being discussed: suggested targets include a small asteroid, an (hypothetical) asteroidal tail and a meteoroid stream.

Cometary nucleus

We observed the comet nucleus from a distance of 8,000–9,000 km. Its surface is largely masked by clouds; therefore, careful photometry with comparative analysis of different images is necessary to extract the properties of the surface itself. Here we list some properties of the nucleus which have been ascertained from preliminary analysis of the data.

Size, shape and rotation. The nucleus is an elongate body with a long axis measuring $14 \pm 1 \text{ km}$ and short axis $7.5 \pm 1 \text{ km}$ (ref. 6). Although it is curved and irregular, a double or multiple nucleus structure (more than one separate body) is almost certainly excluded. A rotation period of $53 \pm 3 \text{ h}$ was obtained from a comparison of images obtained from Vega 1 and Vega 2 (ref. 6).

Reflectivity. First estimates based on the measured brightness⁶ gave a geometrical albedo of $0.04^{+0.02}_{-0.01}$; this value could reflect the influence of dust clouds above the surface of the nucleus. We can estimate the albedo another way: at a distance of 11 AU, when comet Halley was discovered in this apparition⁷, it appeared as an unresolved object, and we can suppose that only the inactive nucleus was then being observed. From photometry⁷ of Halley at this distance, the product of the albedo p and projected surface area S was found to be $\sim 4 \text{ km}^2$. If we approximate the surface projection by an ellipse, $14 \times 7.5 \text{ km}$, then $S = 82 \text{ km}^2$ and $p \approx 0.05$, which agrees well with the direct evalu-

ation mentioned above. This agreement may signify a small average optical thickness of dust clouds above the surface (optical depth $\tau < 1$). In any case the mean reflectivity of the nucleus surface is at least as low as that of the surface of the Moon. If some activity existed at 11 AU, the second evaluation of p is only an upper limit. The observed phase-angle dependence of the brightness of the nucleus⁶ is typical of a Moon-like surface, and is scarcely compatible with a large optical depth of coma dust above the surface.

Temperature. One of the most important new results is the detection by the IKS instrument of infrared radiation from the nucleus region⁸. Again, the influence of coma dust (located immediately above the surface) may be significant. The temperature of the nucleus region is 300–400 K—much greater than predicted by ice models of the nucleus (180–200 K; see, for example, ref. 4). For a black surface, radiative thermal balance gives at this distance from the Sun (0.8 AU) an even higher temperature than was measured, but evaporation of ices must lead to a strong cooling effect. Ices (H_2O and probably others) must be present in the nucleus to provide the gas in the coma. To explain the observed H_2O gas production (see below) it is necessary to suppose that evaporation takes place from the entire illuminated surface, and that about half of the incoming solar energy is converted to heat of evaporation. How then do we explain the high infrared temperature?

Porous refractory surface layer? The conflicting observations of a high surface temperature and the presence of ice may be reconciled if the surface of the nucleus is covered by a thin, insulating layer of a black, porous, refractory substance. There can be ice on the lower boundary of this layer, at a temperature of $\sim 200 \text{ K}$, while the external boundary is 100–150 K warmer. This external boundary layer receives the solar flux and transfers heat downward through the porous layer, and vapour can move upward through it by diffusion. If the entire surface is covered by such a layer, of thermal conductivity $\sim 7 \times 10^3 \text{ erg } ^\circ\text{C cm}^{-1} \text{ s}^{-1}$ (typical value for the martian regolith⁹), we calculate a layer thickness of $\sim 1 \text{ cm}$. The presence of a porous surface layer may provide the explanation of observed irregularities in cometary activity, in the temporary closure of pathways for vapour diffusion, followed by the sudden formation of breaks in the surface layer. The probable existence of such a surface layer (or 'mantle') has been widely discussed in recent years, but one of the most recent models (the 'friable sponge' model) has led to the conclusion¹⁰ that, given the measured gas production, Halley cannot have a mantle at 0.8 AU. However, these calculations assume a value for the mantle thermal conductivity which may be too low.

Concluding remarks. In 1950, Whipple¹¹ proposed that the cometary nucleus is a single solid body of icy conglomerate, composed of a mixture of frozen gases and stony meteoritic material. This model has been the most popular in recent years, but other possibilities, such as many-body models, which describe the nucleus as a collection of gravitationally bound¹² or unbound¹³ small bodies, could not be ruled out. We suggest that the properties of the Halley nucleus observed in the Vega encounters virtually eliminate this second type of model, at least in the case of comet Halley.

Neutral gas and dust

A gas production rate, $Q \approx 1.3 \times 10^{30} \text{ molecules s}^{-1}$ (mass production rate $dM/dt \approx 40 \text{ tonne s}^{-1}$ if the gas is H_2O) was determined by *in situ* measurements on Vega 1 and Vega 2 (ref. 14). In the internal part of the coma ($< 500 \text{ km}$ from the nucleus), H_2O and CO_2 were identified by their infrared spectra (IKS⁸ and TKS¹⁵ experiments). Preliminary estimates of $Q_{\text{H}_2\text{O}}$ from spectra are compatible with *in situ* measurements. CO_2 is probably the second most abundant species after H_2O in the set of parent molecules. Many secondary species (such as OH, C_2 , CH, CN, NH) were revealed by numerous spectra obtained by TKS. Analysis of these spectra will provide the first observational

Table 2 Scientific payload of the Vega spacecraft

Acronym	Instrument	Goal and instrument parameters	Mass (kg)	Ref.
Optical experiments				
TVS	TV system	Inner coma and nucleus imaging. Two CCD* cameras (fields of view, $0.43^\circ \times 0.57^\circ$ and $3.5^\circ \times 5.3^\circ$)	32	6
TKS	Three-channel spectrometer	Spectral mapping of coma emissions in the range $0.12 < \lambda < 1.9 \mu\text{m}$	14	15, 33
IKS	Infrared spectrometer	Detection of infrared emissions of coma and thermal radiation of nucleus ($2, 5 < \lambda < 12 \mu\text{m}$)	18	8
ASP-G	Automatic pointing platform	Pointing of TVS, TKS, IKS at nucleus region	82	34
In situ dust experiments				
PUMA	Dust mass spectrometer	Dust particle elemental composition	19	22
SP-1	Dust particle counter	Dust particle flux and mass spectrum ($m > 10^{-16} \text{ g}$)	2	18
SP-2	Dust particle counter	Dust particle flux and mass spectrum ($m > 10^{-16} \text{ g}$)	4	16
DUCMA	Dust particle detector	Dust particle flux and mass spectrum ($m > 1.5 \times 10^{-13} \text{ g}$)	3	17
FOTON	Dust particle detector	Large dust particle detection (under anti-dust shield)	2	35
In situ analysis of neutral gas, plasma and fields				
ING	Neutral gas mass spectrometer	Neutral gas composition	7	36
PLASMAG	Cometary plasma spectrometer	Ion flux composition, energy spectra of ions and electrons	9	14
TÜNDE-M	Energetic particle analyser	Energy and flux of accelerated cometary ions	5	24
MISCHA	Magnetometer	Magnetic field	4	26
APV-N	Wave and plasma analyser	Plasma waves, 0.01–1,000 Hz, plasma ion flux fluctuations	5	27
APV-V	Wave and plasma analyser	Plasma waves, 0–300 kHz, plasma density and temperature	3	37

* Charge-coupled device.

information concerning the detailed chemistry of the inner coma. *In situ* measurements of dust particle fluxes in the mass range $10^{-16} < m < 10^{-6} \text{ g}$ suggest total dust production rates of 10^7 g s^{-1} at the time of the Vega 1 encounter and $5 \times 10^6 \text{ g s}^{-1}$ for the Vega 2 encounter¹⁶. Preliminary estimates based on the analysis of TKS data¹⁵ are in approximate agreement. From the measured gas production rates, we observe that the dust-to-gas ratio μ varies in the range $0.1 < \mu < 0.25$.

There is reasonable agreement between different dust counters, except that the very large and sharp increase in dust concentration registered by the DUCMA experiment¹⁷ on Vega 1 near the point of closest approach was not detected by the other dust counters.

Strong asymmetry in the dust outflow is visible in television images of frame size $\sim 1,000 \text{ km}$. The dust distribution is also strongly structured, mainly due to jet formation, but the dust fluxes inside jets are enhanced by no more than a factor of 3, and the characteristic spatial scale of jet structures along the spacecraft trajectory is $\sim 10^3$ – 10^4 km . It was possible, with the help of television images, to trace one of these jets to a particular spot on the surface of the nucleus, and thus to calculate the sense and period of rotation of the nucleus, and the mass dependence of dust particle velocity¹⁸, which agrees satisfactorily with a theoretical calculation¹⁹.

In spite of the fact that the first dust particles were detected at a distance of $\sim 3.2 \times 10^5 \text{ km}$ from the nucleus, the sharp increase in number density of dust particles in the mass range 10^{-16} – 10^{-15} g which may be interpreted as the inbound crossing of the dust paraboloid (see ref. 18) for small particles took place at a distance of only $\sim 1.5 \times 10^5 \text{ km}$. This corresponds to a paraboloid apex located at $\sim 4.5 \times 10^4 \text{ km}$ from the nucleus, in agreement with theoretical estimates⁵. For larger masses, $m \approx 10^{-14}$ – 10^{-12} g , the boundary of the dust coma moves closer to the comet. This may be the result of enhancement of the light pressure effect for such particles, due to Mie resonances. Nevertheless, the doubts that existed before the Halley encounters concerning the possibility of detecting particles of sub-micrometre size²⁰ have not been substantiated.

Some preliminary results have been obtained^{16–18} concerning the dust size distribution function. Contrary to previous dust models (see, for example, ref. 21), which on the basis of photometric data predicted a fall-off in the distribution function at

masses $< 10^{-14} \text{ g}$, dust particles have been registered down to the smallest detectable mass, $\sim 10^{-16} \text{ g}$. The slope of the distribution function increases at larger masses, but even at the largest registered mass, $\sim 10^{-6} \text{ g}$, it is still flatter than was predicted by theoretical models¹⁶.

The chemical composition of dust particles has been analysed by the dust mass spectrometer, PUMA²². In order to extend the range of analysed masses to $m > 10^{-12} \text{ g}$, the energy of ions analysed by PUMA in one mode of operation was restricted to a narrow energy range, of width 10 eV. As stated in ref. 23, this greatly reduces the spread of starting times of different ions caused by disturbance of the accelerating electric field by the ion cloud space charge. More than 1,000 spectra have been obtained, which are preliminarily classified into three different groups: (1) spectra of particles with an elemental composition reminiscent of type C1 carbonaceous chondrites (C, O, Na, Mg, Si, Ca, Fe); (2) spectra that differ from group (1) spectra by the presence of considerable carbon (^{12}C and ^{13}C) and nitrogen; and (3) spectra of H_2O or $\text{H}_2\text{O}/\text{CO}_2$ -clathrate ice (mainly H, C and O). An infrared emission band observed by IKS⁸ at 9–11 μm has been tentatively interpreted as due to silicates, and a 7.5- μm emission as reflecting the presence of C–C bonds.

Solar-wind interactions

Cometary ions picked up by the solar wind were detected by the TÜNDE-M²⁴ and PLASMAG¹⁴ experiments at a distance of 10^7 km from the comet. These ions start to drift across magnetic field lines with the solar-wind plasma in a self-consistent electric field, and have a very small initial velocity ($\sim 1 \text{ km s}^{-1}$) in the direction of the magnetic field lines. Thus they form a beam in the solar-wind plasma, exciting Alfvén waves due to the ion-cyclotron instability²⁵. Alfvén waves with frequencies of $\sim 10^{-2} \text{ Hz}$ excited by picked-up ions were detected by the MISCHA magnetometer²⁶, starting at a distance of 3–3.5 $\times 10^6 \text{ km}$ from the comet.

The long-wavelength magnetohydrodynamic turbulence resulting from the Alfvén-wave nonlinear interaction is probably responsible for the stochastic Fermi acceleration of high-energy ($\sim 540 \text{ keV}$) ions detected by the TÜNDE-M experiment on Vega 1 at 10^6 km from the comet.

The inbound crossings of the bow shock by Vega 1 and Vega 2 at $\sim 10^6 \text{ km}$ from the comet are registered by the plasma¹⁴,

low-frequency plasma wave²⁷ and magnetometer²⁶ experiments. The bow shock standoff distance is consistent with theoretical estimates based on solar-wind mass loading arguments^{28,29}, if one takes into account that, according to the kinetic description of picked-up cometary ions with an isotropic velocity distribution²⁵, the mass loading in front of a Mach $M = 2$ shock will be 1.75 times higher than that calculated for gas-dynamic flow with specific heat ratio $\gamma = 5/3$, corresponding to this case.

The problem of cometary bow shock structure has great importance for the physics of collisionless shocks in a plasma, the first theory of which emerged in 1959³⁰. The shock registered at Vega 1 is identified by a sharp enhancement of extremely-low-frequency (ELF) waves and a jump in magnetic field strength. Thus it is similar to the strong quasi-perpendicular Earth bow shock, the only difference being that the role of ions reflected from the shock front is played here by cometary ions, which leak easily from shocked to unperturbed solar wind, where they are accelerated in a self-consistent electric field³¹. The inbound crossing of the bow shock by Vega 2 is characterized by a smooth increase in plasma waves and plasma heating. This is consistent with an almost field-aligned solar-wind plasma flow, in which case the cometary shock is similar to the cosmic-ray shock and the energy dissipation is caused by the thermal conductivity of cometary ions²⁵.

The continuing solar-wind loading by cometary ions behind the shock results in a gradual deceleration of the plasma flow and a magnetic field build-up. Both Vega 1 and Vega 2 reached the outer edge of a thick magnetic barrier separating loaded solar-wind flow from unmagnetized outflow of cometary plasma. The maximum magnetic field reached here was ~ 75 nT at both spacecraft. A sudden increase in cometary plasma density was registered by the PLASMAG experiment at a distance of $\sim 40,000$ km from the cometary nucleus. Simultaneous observation of high fluxes of suprathermal electrons with ~ 1 keV energy and low-frequency (~ 15 Hz) plasma waves indicate the occurrence of the critical velocity ionization phenomenon of Alfvén in cometary comae³².

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Television observations of comet Halley from Vega spacecraft

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The television system (TVS) aboard the spacecraft Vega 1 and Vega 2 observed comet Halley from 4 to 11 March 1986, and transmitted $\sim 1,500$ images to Earth. The best images of the cometary nucleus were obtained from distances of 8,000-9,000 km. The nucleus is an irregular potato-shaped body, $\sim 14 \times 7.5 \times 7.5$ km in size, which rotates with a period of 53 ± 3 h. The surface is rather dark; the measured albedo is $\sim 0.04^{+0.02}_{-0.01}$. Active emission of matter was observed on the sunlit side of the nucleus.

The main objectives of the TVS experiment were: (1) to ascertain whether the cometary nucleus is a consolidated body, and to assess its size, shape and rotation; (2) to evaluate the composition and texture of the nucleus surface; (3) to identify the spatial and temporal pattern of jet activity; and (4) to study the structure and dynamics of the near-nucleus coma.

Highest priority was given to the determination of the shape and volume of the nucleus. Hence, a relatively safe trajectory was chosen for the spacecraft, which allowed us to observe the nucleus from different viewing angles. The unknown and hazardous conditions, especially at closest approach, required an adaptive television system and real-time data transmission to Earth; the rapid (up to 1° per s) change of viewing angle required an automatic pointing system with on-board intelligence. Photometry was based on pre- and in-flight calibration.

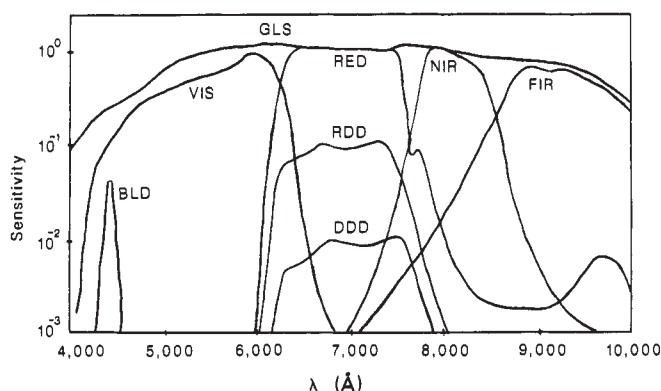


Fig. 1 Spectral sensitivity of the TVS camera, for the different filters used for imaging.

Fig. 2 Fly-by configuration of the Vega spacecraft and comet nucleus: as shown, the encounter took place above the ecliptic plane. The nucleus is drawn as it was during the Vega 1 encounter. The relative velocity was $79.222 (76.785) \text{ km s}^{-1}$ for Vega 1(2). The angles β and α are the view angles of the pointing platform (measured in and perpendicular to the spacecraft orbital plane) and Δ is the phase angle (see also Fig. 3). P is the point of closest approach, reached by Vega 1 (2) at 7:20:06 UT on 6 March (7:20:00 on 9 March). The spacecraft crossed the solar meridian plane (M) 41 (43.5) s after closest approach.

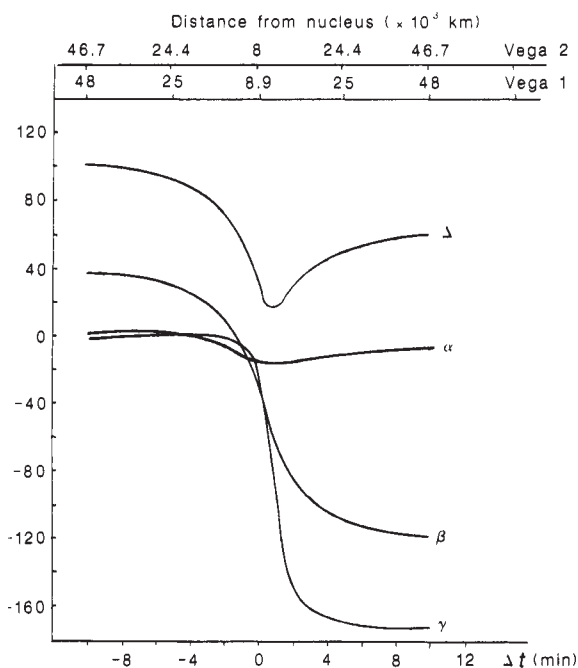
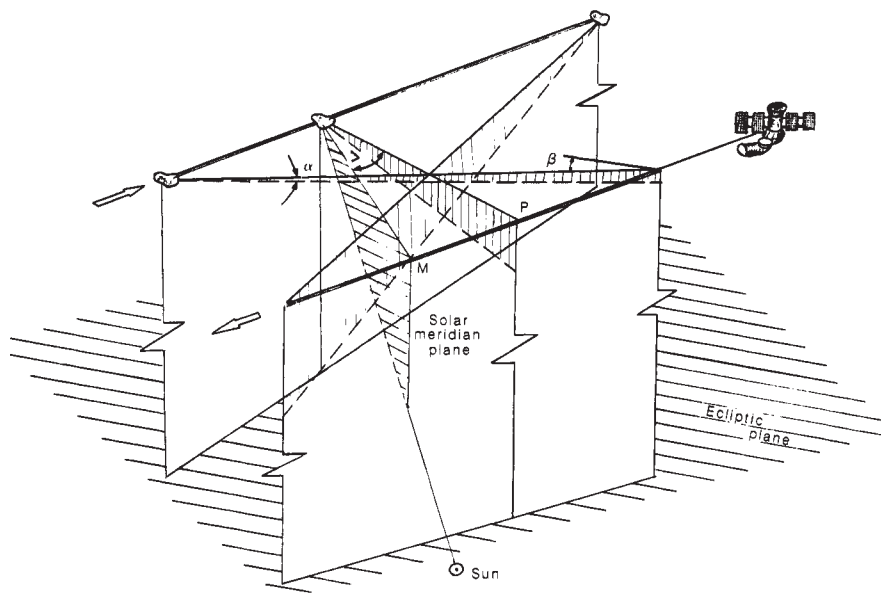


Fig. 3 Variation with time (relative to the time of closest approach) of the phase angle Δ , the angle γ , which is the angle between the horizontal image axis and the projection of the Sun direction onto the image plane, and the pointing platform viewing angles α and β (see Fig. 2). The time scales are nearly identical for Vega 1 and Vega 2; the distances are given separately.

Based on the above requirements and the expected characteristics of Halley¹, the TVS was designed as a two-camera (focal lengths 1,200 and 150 mm), four-channel system with CCD (charge-coupled device) imagers of angular resolution ~ 3.5 and 28 arcs (ref. 2).

The narrow-angle camera could generate images in six different spectral bands in the range 400–1,100 nm (Fig. 1), whereas the wide-angle camera was restricted to the region between 630 and 760 nm, where the cometary gas emission is known to be least intense, and thus the nucleus/coma contrast should be greatest. Exposure times were selected automatically.

Detailed pre-launch calibration made it possible to specify the absolute spectral photometric characteristics of each CCD array element and to correct the data for CCD behaviour (for

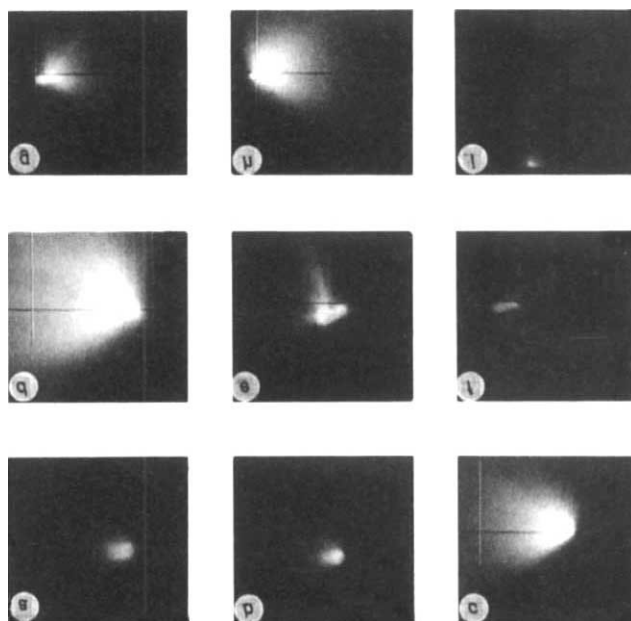
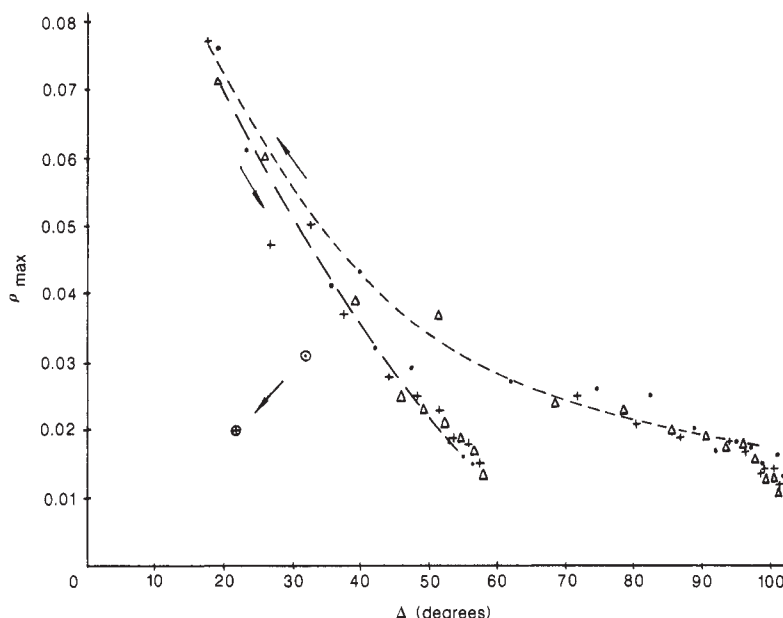


Fig. 4 Unprocessed images taken from Vega 2. For each image, the date, time (UT), filter, spacecraft-comet distance (km), pixel size (on the nucleus, in km) and image size (km) are as follows: a, 7 March, 04:15:48, GLS, 1.4×10^7 , 210×280 , $2.69 \times 10^4 \times 3.58 \times 10^4$; b, 9 March, 05:49:52, NIR, 419,920, 6.30×8.40 , $806 \times 1,075$; c, 9 March, 07:13:47, NIR, 29,746, 0.446×0.595 , 228×305 ; d, 9 March, 07:18:18, NIR, 11,222, 0.168×0.224 , 86.0×115 ; e, 9 March, 07:19:58, NIR, 8,045, 0.121×0.161 , 62.0×82.4 ; f, 9 March, 07:21:39, VIS, 11,060, 0.166×0.221 , 85.0×113 ; g, 9 March, 07:23:07, RED, 16,454, 0.247×0.329 , 127×168 ; h, 9 March, 07:26:11, NIR, 29,600, 0.444×0.592 , 227×303 ; i, 11 March, 06:13:12, GLS, 1.3×10^7 , 194×259 , $9.95 \times 10^4 \times 1.33 \times 10^5$.

example, modular transfer function and charge transfer efficiency).

The TVS was placed on a pointing platform which could rotate $\pm 110^\circ$ in the ecliptic plane (azimuth) and $\pm 60^\circ$ normal to it (pitch). During the encounter the TVS controlled the pointing of the platform. Each platform also carried a pointing sensor built around an eight-element photodiode array (ADN-8), as a back-up for pointing. Although reliable and fast, this back-up circuit is inferior, because its operation depends

Fig. 5 Bidirectional reflectance factor, $\rho_{\max}$, of the nucleus in different spectral bands, as a function of phase angle Δ , before (---) and after (—) Vega 1 closest approach (+, VIS; Δ , RED; $\bullet$, NIR), and for two values of Δ after Vega 2 closest approach ($\oplus$, VIS; $\circ$, NIR). Arrows show the direction of time. $\rho_{\max}$ is defined as $B_{\max}/F_{\odot}$, where $B_{\max}$ is the maximum brightness of the nucleus recovered from the respective fragment of the image, and $F_{\odot}$ is the solar radiation intensity in the respective spectral band of TVS sensitivity. These $B_{\max}$ estimates are averaged over an image fragment 3×3 pixels in size, which corresponds to a nucleus surface area of $0.2\text{--}2\text{ km}^2$, depending on distance to the nucleus. Because the brightest regions of the nucleus may be zones of active emission, the reflectance obtained may be due, at least in part, to particles leaving the nucleus surface, which most probably have a higher reflectivity. In this case the estimates of $\rho_{\max}$ should be regarded as upper bounds. The differences between the $\rho_{\max}$ values before and after Vega 1 closest approach, and between the Vega 1 and Vega 2 results, are too large to be explained by the TVS sensitivity reduction recorded during repeated calibration against Jupiter, which may have been caused by the impact of the dust particles of the coma on the camera lens. These differences may be caused by the variation of dust density with changing camera angle, by changing dust activity, and/or by non-uniform reflectance of the nucleus surface.



strongly on the brightness field pattern of the scene and points the platform only to the integral centre of the brightness field.

The functioning and calibration of the systems were checked at 2-month intervals after launch. In addition, from 14 to 22 February 1986, after the platforms had been deployed into operational position, images of Jupiter and its satellites and of Saturn were taken to check the system performance and to improve the reference axis of the platform and cameras relative to the inertial coordinates. (This was required for the Pathfinder project³). Similar imaging was carried out on 26 and 27 March, long after the encounter.

The experiment began on 4 (7) March for Vega 1 (2), at a distance of $\sim 1.4 \times 10^7$ km. Observations were made every day until 11 March.

The TVS controlled the pointing platform in two different modes: at distances $> 5 \times 10^4$ km, attitude error was kept to < 5 arc min and at smaller distances, in addition to this requirement, the tracking error was minimized. During the Vega 2 fly-by, the pointing had to be controlled by the ADN-8 brightness-maximum sensor from 32 min before closest approach, because the TVS pointing processor had failed.

The observation program comprised several stages. During the first, which began at 1.4×10^7 km, the view angle was nearly constant and the nucleus was not resolved. The second stage started at a distance of 9×10^4 km (20 min before closest approach): here the view angle changed considerably and the linear dimensions of the nucleus image increased from 2–4 to 12–16 pixels. The third stage, at distances $< 5 \times 10^4$ km, was characterized by fast changes of view and phase angle (Figs 2, 3), and the nucleus image size reached a maximum. After the encounter the program was repeated in reverse order.

During the Vega 1 closest approach, the number of spectral bands was reduced to the combination NIR, VIS, RED (Fig. 1), and images were framed in a 'floating window' of 128×128 pixels. For Vega 2, full-frame images (512×512 pixels) were transmitted using the filters Glass, VIS, NIR and RED. To improve the recognition of coma morphology from distances $> 5 \times 10^4$ km, occasional overexposed images were taken.

Figure 4 shows a sequence of unprocessed images obtained during the Vega 2 encounter. An image of the coma taken at a distance of 1.4×10^7 km (not shown) shows it to have a characteristic paraboloid shape, formed by the trajectories of particles emitted from the nucleus. The phase angle was 108° , and the paraboloid apex for the $10^{-6} \text{ W cm}^{-2} \text{ s}^{-1} \mu\text{m}^{-1}$ isophote is at a distance of 3×10^4 km from the brightness maximum, in the

sunward direction. Brighter isophotes $< 1.5 \times 10^4$ km from the nucleus are asymmetrical, and this asymmetry increases as the distance from the nucleus decreases (see Fig. 4).

In closer images (Fig. 4e) one part of the nucleus appears to be more active than the rest. Distinct jets are identifiable in the images, and at least five jets are observed in the time interval ~ 600 to $+600$ s (relative to closest approach). In some of the images, some of the jets are observed to have multiple components; additional finer structure also seems to be present. All of the jets are directed towards the hemisphere which includes the Sun.

A notable feature of the observed emission pattern is the variation of the isophote shape in images taken from the same view angle, but separated by an interval of 72 h, at distances $< 7 \times 10^6$ km. This variation may be the result of the rotation of an elongate nucleus.

Figure 5 shows the bidirectional reflectance factor, $\rho_{\max}$ (defined in the Fig. 5 legend), estimated as a function of phase angle Δ . The results imply not only the low reflectance of the nucleus but also the absence of considerable differences between

Fig. 6 (Opposite, top) a, False-colour image taken by Vega 2 at a distance of $\sim 8,030$ km from the nucleus, 1.5 s before closest approach, with $\Delta = 32^\circ$. b, Contour plot of the bidirectional reflectance factor ($\rho_{\max}$) of the nucleus area. c, Interpretation of jet structure, showing five strong jets and a possible region of jet activity. Jets 1 and 2 probably originate from the central part of the larger end of the nucleus, and point to within 30° of the Sun.

Fig. 7 (Opposite, bottom) Processed images taken from Vega 1 on 6 March 1986, showing the nuclear region. The nucleus shape was approximated using an adaptive bidirectional gradient algorithm which takes into account the differences of brightness distribution models for the intranuclear and near-nuclear regions. The apparent shape is strongly dependent on the Sun illumination angle. Once the nucleus shape had been defined, the image brightness field was processed by a texture enhancement procedure. Image parameters [as in Fig. 4 legend, except time is relative to closest approach (min:s)]: a, $-1:53$, RED, $12,567$, 0.188×0.188 , 18.2×16.0 ; b, $-1:16$, VIS, $10,701$, 0.161×0.161 , 15.6×13.7 ; c, $-0:57$, RED, $9,944$, 0.149×0.149 , 14.6×12.7 ; d, $-0:12$, VIS, $8,936$, 0.134×0.134 , 13.0×11.4 ; e, $+0:30$, NIR, $9,223$, 0.138×0.138 , 13.4×11.7 ; f, $+0:48$, VIS, $9,700$, 0.145×0.145 , 14.1×12.3 ; g, $+1:02$, RED, $10,196$, 0.153×0.153 , 14.8×13.0 ; h, $+1:25$, NIR, $11,201$, 0.168×0.168 , 16.3×14.3 ; i, $+1:59$, RED, $13,011$, 0.195×0.195 , 18.9×16.6 ; j, $+2:58$, RED, $16,732$, 0.251×0.251 , 24.3×21.3 ; k, $+3:26$, NIR, $18,649$, 0.280×0.280 , 27.2×23.8 ; l, $+3:43$, VIS, $19,845$, 0.298×0.298 , 28.9×25.3 .



Fig. 6

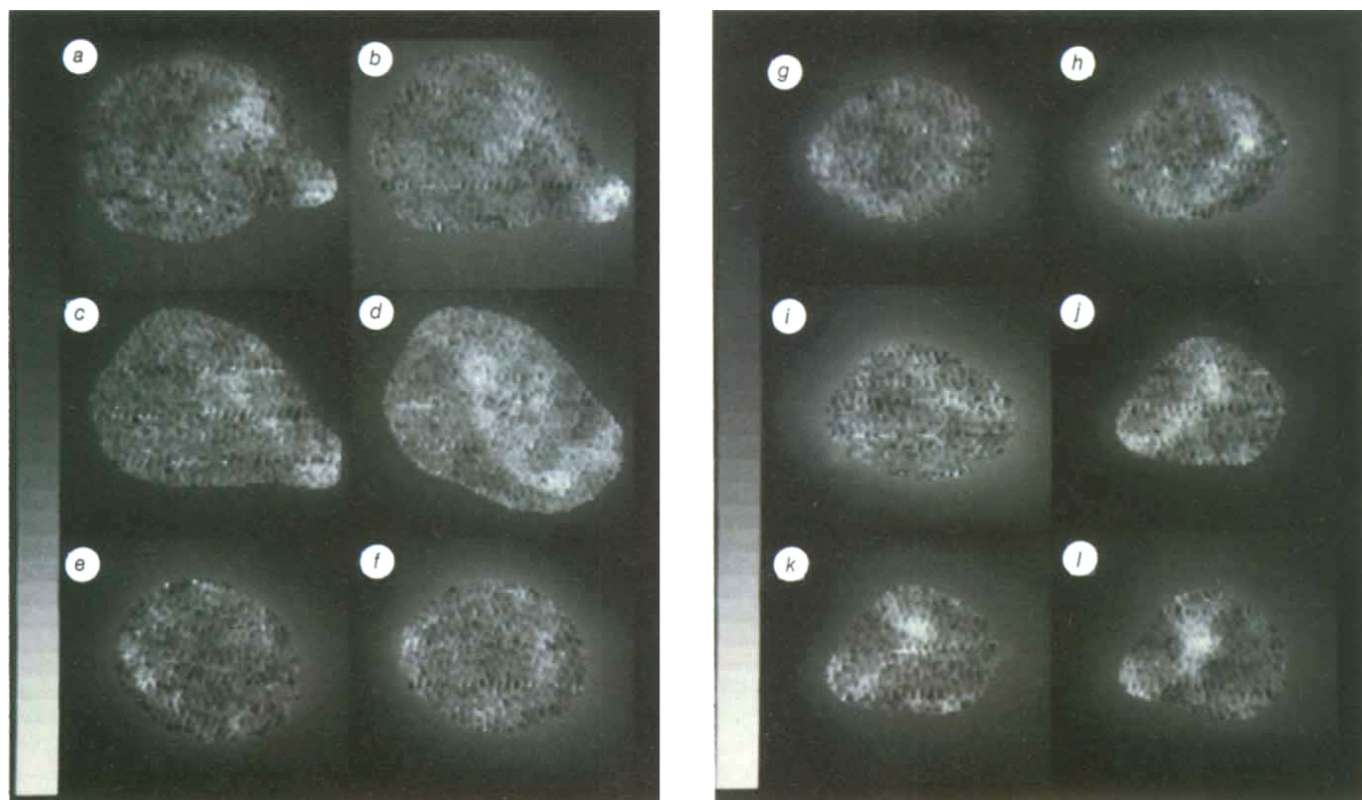


Fig. 7

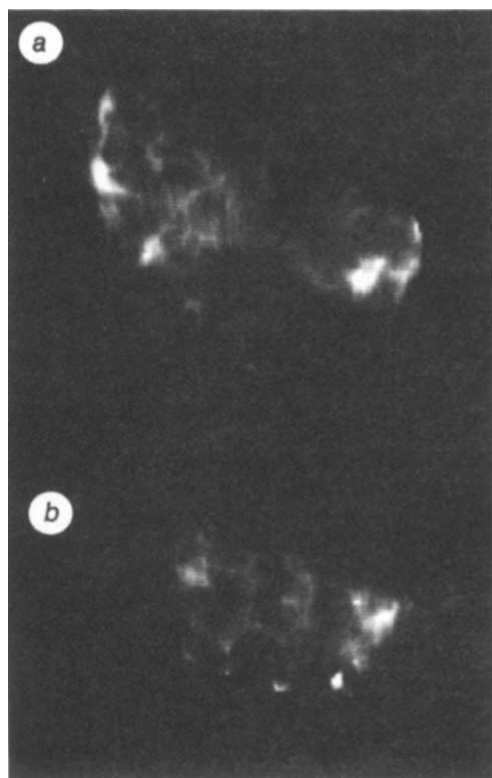


Fig. 8 Images of the nuclear region taken from Vega 2 on 9 March 1986, processed as described in Fig. 7 legend. Image parameters (as in Fig. 7 legend): *a*, $-0:01.5$, NIR, 8,050, 0.120×0.120 , 23.6×15.5 ; *b*, $+1:38.7$, VIS, 10,660, 0.160×0.160 , 31.0×20.0 .

the reflectances measured in the three spectral regions (450–650, 630–760 and 760–860 nm). The sharp increase in reflectance at small phase angles is similar to that observed in the scattering indicatrix of the Moon's surface.

Variations in $\rho_{\max}$ over the nucleus (Fig. 6*b*) are caused by the variation in irradiance of different areas, as a function of surface slope. Characteristic isophote variations are caused by inhomogeneities in the nucleus/coma system.

The mean $\rho_{\max}$ of the nucleus at $\Delta = 32^\circ$ is ~ 0.02 . Assuming that at small phase angles ($\Delta < 17^\circ$) (at which no observations from the Vega spacecraft were made), the phase function of the nucleus surface is similar to that of the Moon, the geometric albedo of the nucleus has been calculated to be $p = 0.04^{+0.02}_{-0.01}$. According to the model discussed below, the visible area of the nucleus S_v may vary from 40 to 80 km² due to rotation. Because of this variation, an observer located in a plane normal to the nucleus spin axis should see a brightness variation of ~ 0.7 mag. The measured pS_v ranges from 1.9 to 3.8 km², which agrees with the mean value of the Halley nucleus stellar magnitude, 13.9 ± 0.5 , measured from Earth, at large (> 8 AU) heliocentric distances^{4,5}.

An albedo of 0.04 is similar to that observed for the rings of Uranus, the newly discovered satellites of Uranus (for example, 1985U1; B.S., personal communication) and the darker regions of Iapetus. It is reasonable to assume that all of this material is carbonaceous in composition; that is, that we are seeing primitive material accreted during the very early history of the Solar System. These results also indicate that fresh ice is covered either by a regolith or porous mantle of dark, refractory material, or that there exists a geometrically thin, but optically thick, layer of suspended dust surrounding the nucleus. At this time, we are unable to distinguish among these models.

More than 70 images were obtained of the nucleus, from distances of $< 5 \times 10^4$ km and from different view angles (Figs

7, 8; the change in view angle is 160° in the orbital plane). Because there was less dust between the spacecraft and the nucleus during the second fly-by, the nucleus was seen much more clearly by Vega 2. Three consecutive images taken at -1.5 , $+98.7$ and $+187.3$ s help to define its shape (Figs 8*a, b, 4g*; part of the nucleus on the third image is overexposed). These three images can be correlated assuming that the nucleus was seen broadside when the spacecraft was $40 \pm 5^\circ$ (86^{+17}_{-11} s) past closest approach. To determine the exact shape of the nucleus requires comparative measurements between images, taking into account the effects of phase-angle and possible albedo variations. At this stage the error of our size estimate is $\sim 10\%$. The nucleus is an irregular potato-shaped object, with principal dimensions $(14 \pm 1) \times (7.5 \pm 1) \times (7.5 \pm 1)$ km. From Vega 1 images (Fig. 7) we have reason to assume that the long axis of the nucleus was directed towards the spacecraft ~ 10 s ($\sim 5^\circ$) before closest approach, and from other images it is evident that the larger of the two ends was facing the spacecraft.

From this geometry, assuming direct rotation (that is, in the same sense as the comet's orbital motion), we derive a rotation period of $\sim 53 \pm 3$ h. This value agrees well with that obtained in refs 6 and 7. (For retrograde rotation the period is 44 ± 2 h.)

The rotation axis of the nucleus is within 15° of its axis of greatest moment of inertia (which is approximately perpendicular to the comet's orbital plane): any nutation is confined to a cone of this half-angle. Further image processing will undoubtedly reveal topographic features, avoid some of the shape ambiguities created by the gradient algorithm, and make possible a complete three-dimensional reconstruction of the nucleus⁸.

We thank all the (more than 200) scientists and engineers who contributed to this project.

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Infrared sounding of comet Halley from Vega 1

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The IKS instrument carried by the Vega 1 spacecraft performed infrared sounding of the inner coma and nuclear region of comet Halley. An emissive centre, a few kilometres in size, was detected with a temperature significantly in excess of 300 K. In the surrounding central coma, hydrocarbon species or other carbonaceous material seem to be present. The fluorescence signatures of H₂O and CO₂ were identified.

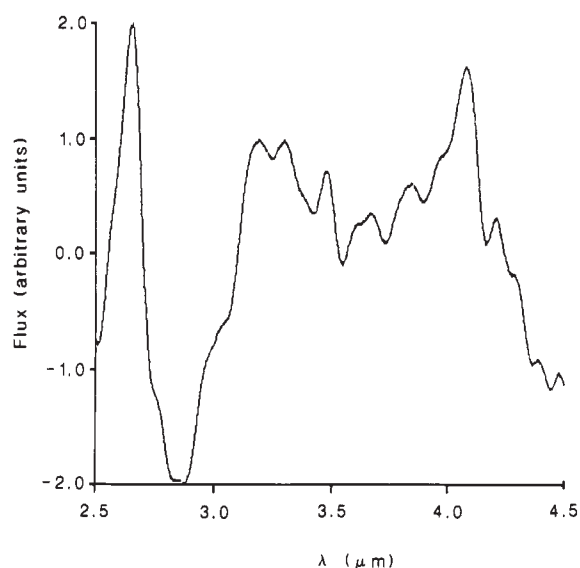


Fig. 1 Spectrum of comet Halley's central region at wavelength $2.5 \leq \lambda \leq 5 \mu\text{m}$, obtained from the difference between spectra recorded at distances of 43,000 and 90,000 km from the comet, in order to remove the instrumental background. Low frequencies have been filtered out of the power spectrum to remove the residual background signal. At a distance of 43,000 km, the observed coma has a diameter of 770 km (or 1 arc s, as seen from the Earth). The mean standard deviation of the data is 0.3 units.

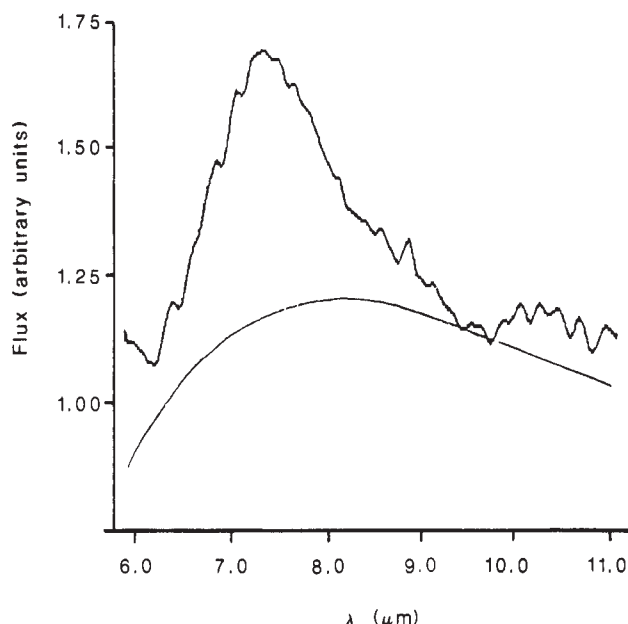


Fig. 2 Spectrum of comet Halley's central region at wavelengths between 6 and 12 μm , obtained from the difference of two spectra acquired at 43,000 and 60,000 km, in order to remove the instrumental background. The smooth line is the spectrum of a black body at 350 K. The mean standard deviation of the data is 0.05 units.

The IKS instrument was designed to record spectra of the inner part of the coma in the spectral ranges 2.5–5 and 6–12 μm ('spectroscopic channels'), and to measure the temperature of the nucleus and its dimensions in two perpendicular directions ('imaging channel'). The instrument is described in ref. 1. The infrared detectors had to be cooled down to $\sim 80 \text{ K}$ to detect the expected weak signals. An active cryogenic system was used, based on the expansion of pressurized gaseous nitrogen.

On Vega 1, the IKS instrument operated successfully. The last available cometary data from the imaging channel were obtained a few minutes after closest approach. For the preliminary analysis of data from the spectroscopic channels, we have used only spectra obtained a few minutes before closest approach, when the distance to the comet was 43,000 km. Near closest approach the data flow was interrupted for $\sim 30 \text{ min}$, due to an erroneous command received by the instrument. No results were obtained from Vega 2 because of failure of the cryogenic system.

Spectroscopy is achieved in two spectral bands by using two circular variable filters (CVF) located on two tracks of the encoding wheel. Each track is divided into two halves to duplicate the spectrum and avoid discontinuities. The resolving power of the CVF is $\lambda/\Delta\lambda = 40$, and the field of view is 1° in diameter. The large apparent size of the source during the fly-by prevented the use of sky chopping to eliminate the large instrument background; the signal is only spectrally modulated by the rotation of the wheel. The cometary signal is superimposed on the background due to the emission of the instrument itself, most of which is eliminated by taking the difference between spectra obtained at different times. Because the cometary signal is expected to vary approximately as r^{-1} (where r is the distance to the nucleus) this difference is, to first order, proportional to the cometary spectrum. After the subtraction, a small residual background signal remains which is due to temperature variations of the instrument. It can be removed using laboratory calibration data and accurate monitoring of the instrument temperature. The minimum detectable intensity is $\sim 5 \times 10^{-8} \text{ W } \mu\text{m}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ at 3 μm , and $6 \times 10^{-7} \text{ W } \mu\text{m}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ at 6 μm . Spectra are added over 18-s intervals, each correspond-

ing to 128 rotations of the filter wheel. An internal black body is used for calibration.

Figure 1 shows a representative spectrum of the 2.5- μm region, obtained at a distance of 43,000 km from the comet. The continuum signal was eliminated by filtering out the low frequencies in the power distribution of the spectrum. The spectrum shows narrow emission features at 2.70 and 4.25 μm which may be attributed to the ν_3 bands of H_2O and CO_2 . A broad emission feature at 3.2–3.4 μm might be due to the C–H vibration of hydrocarbon molecules (an alternative explanation will be given below), and the water-ice absorption signature seems to be

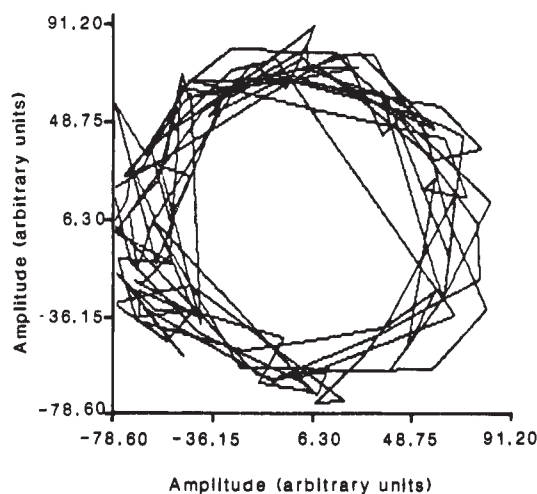


Fig. 3 Phase diagram of the output of one image channel during an 18-s interval. The axes are signal amplitudes. Changes in the position of the nucleus image in the field of view appear as rotations of the phase of the modulated signal. The data points accumulate on a ring, the centre of which is determined by the instrument background and the average radius of which is proportional to the cometary signal.

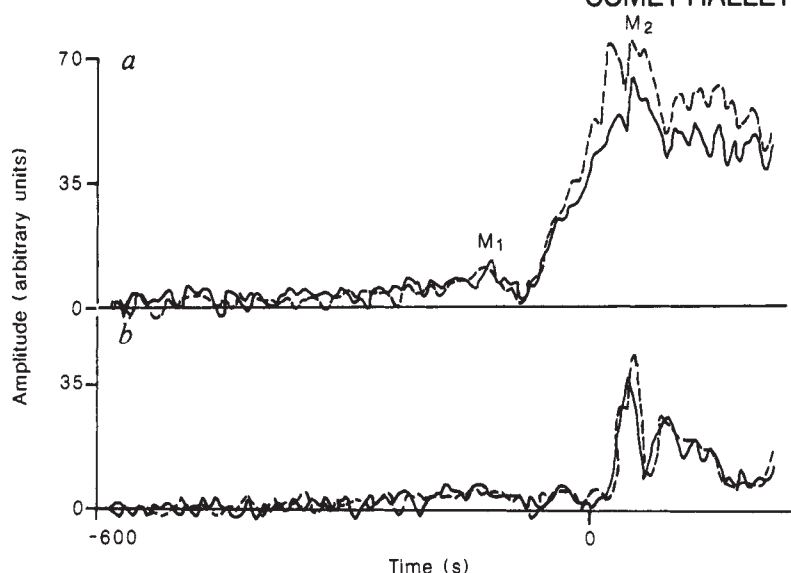


Fig. 4 Outputs of imaging channels I (—) and IV (---) (a) and II (—) and III (---) (b). The time is expressed relative to an arbitrary zero time, which is within 20 s of the time of closest approach. Signals I and IV exhibit two maxima (M_1 and M_2), separated by a well-marked minimum from which the source dimension can be estimated (see text).

present at $\sim 3 \mu\text{m}$. The presence of other molecular emissions is not excluded, but further analysis is needed.

According to fluorescence excitation models^{2,3}, the $2.7\text{-}\mu\text{m}$ feature corresponds to a water production rate of $\sim 10^{30}$ molecules s^{-1} , and the $4.25\text{-}\mu\text{m}$ feature to a CO_2 production rate ~ 100 times lower.

Figure 2 shows a spectrum of the cometary flux between 6 and $12 \mu\text{m}$. A strong and broad emission centred at $7.5 \mu\text{m}$ extends from 6.5 to $9 \mu\text{m}$, and a second weaker emission may be present between 9 and $11 \mu\text{m}$. We tentatively interpret the $9\text{--}11\text{-}\mu\text{m}$ band as being due to silicates and the $7.5\text{-}\mu\text{m}$ emission (not seen from the ground) as representative of the presence of C-C bonds in the nuclear region.

It seems unlikely that the $7.5\text{-}\mu\text{m}$ feature could be due to fluorescence excitation of a gaseous molecule. Indeed, the expected fluorescence rates of all possible molecules are quite low at this wavelength². We note that both the $3.3\text{-}\mu\text{m}$ and $7.5\text{-}\mu\text{m}$ features are present in interstellar medium emission spectra. These features of the comet spectrum could be related to the presence of carbonaceous material including C-H and C-C bonds.

In the IKS imaging channel^{1,4} the image of the comet is formed on a moving grid with an angular period of one minute of arc. The flux emitted by a point-like source is 100% modulated, but when the dimensions of the source image become nearly equal to the period of the grid, the modulation may vanish. Because of variations in the apparent dimensions of the nuclear region during the fly-by, the measured signal should show a succession of maxima and minima, from which one can find the source dimensions in the two directions of analysis of the grid, which are approximately parallel and perpendicular to the comet's orbital plane. These measurements are performed in two infrared bands: $7\text{--}10$ and $9\text{--}14 \mu\text{m}$. Comparisons of the two spectral densities give the colour temperature of the source. Thus, the signal is split into four channels: I (long wavelength, perpendicular), II (long wavelength, parallel), III (short wavelength, parallel) and IV (short wavelength, perpendicular).

As explained in detail in ref. 4, the residual pointing platform jitter produces some randomization of the phase of the modulated signal, whereas the instrument calibration and background signal are unaffected. Therefore, on a phase diagram of each channel output (see Fig. 3), the points of the cometary signal acquired over a short time period must lie on a circle (see Fig. 3 of ref. 4 obtained during ground tests). The data were therefore reduced by plotting phase diagrams of the data, locating the centres of the circles, and computing every 4 s the mean of their radii. The signal emerged clearly from the noise only 5 min before closest approach. Figure 3 shows one of the obtained phase diagrams and Fig. 4 presents the four channel signals.

There is a marked difference between the time variation of signals I and IV and that of II and III (Fig. 4), indicating a non-spherical source. This fact, combined with the rapid variation of the line-of-sight orientation during the encounter, limits the utility of a preliminary analysis based on simple simulation. It is nevertheless possible to interpret the results given by channels I and IV by comparison with simulations of the fly-by using uniformly bright sources of simple shapes⁴. The positions of the first small maximum (M_1 in Fig. 4a), the well-marked minimum and the large maximum (M_2) correspond to an emissive region with an effective dimension of $5.5 \pm 1 \text{ km}$ perpendicular to the comet orbit plane. To explain the ratio of the two maxima, we must assume some strong effect of the quickly changing phase angle and/or a double structure in the emitting source. Such effects must also be taken into account in interpreting the data from channels II and III: this will be done in future, using more realistic and sophisticated models and inversion procedures.

The ratios of signals I/IV and II/III were very similar, indicating that the colour temperature is not a function of the direction of analysis. These ratios are also constant throughout the period when the signal-to-noise ratio is good. The measured values of 0.85 ± 0.02 (I/IV) and 0.83 ± 0.03 (II/III) indicate, on the basis of pre-flight calibration data, a colour temperature of $420 \pm 60 \text{ K}$. However, if the strong spectral features observed by the spectroscopic channels of IKS near $7 \mu\text{m}$ are also present in the small region detected by the image channel, the derived temperature of this region will be $\sim 300\text{--}400 \text{ K}$. In any case, the absolute value of the flux measured by channels I and IV requires a minimum physical source temperature of 300 K (for unit emissivity). These temperatures are well in excess of the sublimation temperature of bare ice; they lie in the range appropriate for absorbing dust, or the surface of a dark body, at a distance of 0.8 AU from the Sun. However, this observation alone does not exclude the presence of subliming ice, the thermal radiation of which would be masked by the higher-temperature contribution⁵. A surface layer of a porous dark substance with a low thermal conductivity, covering the ice, could explain the high measured temperature.

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Spectroscopic study of comet Halley by the Vega 2 three-channel spectrometer

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The three-channel spectrometer (TKS) aboard the Vega 2 spacecraft recorded infrared and visible spectra near the nucleus of comet Halley. Spectra in the range 0.95–1.9 μm at a distance of 300 km from the nucleus reveal the H_2O 1.38- μm band and OH bands, the latter excited by dissociation of a parent molecule. Their production rates are 4×10^{29} and 1.7×10^{30} molecules s^{-1} , respectively. The dust particle density is 0.35 g cm^{-3} , typical of fluffy particles of interplanetary dust. Emissions of 10 species are observed in the range 275–715 nm at $\sim 4,000$ km from the nucleus, and 6 of them are analysed in terms of production rates: $Q_{\text{OH}} = 2 \times 10^{30}$, $Q_{\text{CH}} = 10^{29}$, $Q_{\text{C}_2} = 6 \times 10^{27}$, $Q_{\text{C}_3} = 3 \times 10^{27}$, $Q_{\text{CN}} = 10^{27}$ and $Q_{\text{NH}} = 2 \times 10^{26}$, all in molecules s^{-1} . The difference between the OH and H_2O production rates is puzzling and needs further analysis. Ionic emissions, not discussed here, are prominent in the tailward part of the comet.

The TKS is a combination of three spectrometers: infrared (IR), near-ultraviolet and visible (V) and ultraviolet (UV), with some shared instrumentation. The spectral ranges are 950–1,900, 275–715 and 120–290 nm, respectively. The resolving power is $\lambda/\Delta\lambda = 70$ for IR and 185 for V and UV, and the detection limits are 800 kR (kilorayleigh; $1 \text{ R} = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1}$

$(4\pi \text{ sr})^{-1}$) for IR and 0.2 kR for V. The field of view at a distance of 8,000 km is $230 \times 23 \text{ km}$ for IR and $46 \times 2 \text{ km}$ for V.

The UV and V channels employ concave holographic gratings and intensified CCD (charge-coupled device) linear arrays with 1,024 elements, whereas the IR spectrometer uses a circular variable filter. Tilting of the Cassegrain telescope secondary mirror results in scanning the space contained in a frame of angular dimensions $2^\circ \times 1.5^\circ$, with 7 lines and 15 positions in every line; one step equals 19 km at the point of closest approach. A detailed description of the instrument is given in ref. 1.

The Vega 2 TKS measured spectra in the infrared and visible ranges; the UV channel did not function. On Vega 1 the TKS failed completely, due to electronic damage.

Figure 1 shows the infrared spectrum of the comet, obtained by averaging individual spectra with weights proportional to the total IR intensity; this procedure gives prominence to spectra obtained near the nucleus. Our preliminary estimate is that the spectrum in Fig. 1 refers to a distance of 300 km from the nucleus. All values given below have uncertainties of a factor of 2. The spectrum exhibits a decrease in intensity by a factor of 5 as the wavelength λ increases from 0.95 to 1.8 μm ; the brightness coefficient $R = \pi I/I_\odot$ is constant, at $\sim 10^{-4}$. The continuum radiation is due to cometary dust scattering. For a dust particle size spectrum given by $n = ar^{-u}$, where n is the number density of particles with radius $> r$, and for refraction and absorption indices independent of wavelength, the brightness coefficient of the dust medium is $R = A\lambda^{-u+2}$, where A is a constant of proportionality². Thus the spectrum in Fig. 1 implies $u = 2$. However, the size spectrum should start to decrease more steeply at some radius r_{max} , for the total mass of the dust not to be divergent with $u \leq 3$. If one takes $r_{\text{max}} \approx 30 \mu\text{m}$, similar to that of interplanetary dust³, then R independent of λ implies $u \leq 2$. *In situ* measurements⁴ give $u \approx 2$, and a total dust production rate of 5 tonnes s^{-1} . Comparison with our data results in an estimate for the dust particle density of 0.35 g cm^{-3} , typical of fluffy particles of interplanetary dust³. The isotropic flow model used to calculate the production rate is appropriate for the analysis of our averaged spectrum, although the real flow is predominantly in the sunward direction.

One of the objectives of the experiment was the detection of the H_2O 1.38- μm band. Although all models of comets presume

Fig. 1 Average near-infrared spectrum of comet Halley. The solar spectrum $I_\odot$ is shown for comparison. Positions of vibrational transitions are labelled with the vibrational quantum numbers (v) of the upper and lower states. The spectrum in the interval 1.14–1.25 μm is measured twice, and the difference between the two spectra is a measure of the experimental error.

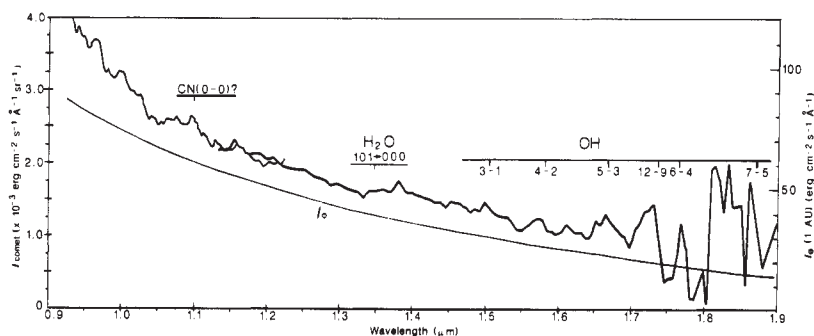


Table 1 Parameters of comet Halley species derived from spectrum b (Fig. 2)

Species	OH	CH	C ₂	C ₃	CN	NH
λ (Å)	3090	4310	5165	4050	3883	3360
g (s^{-1})	3×10^{-4}	0.016	0.038	0.2	0.093	0.053
l (km)	1.5×10^5	90	1.2×10^5	5.4×10^4	3×10^5	10^5
l_p (km)	10^5	3.7×10^4	3×10^4	10^3	2.2×10^4	5×10^3
$4\pi I$ (kR)	1350	24	475	42	300	67
N (molecules cm^{-2})	3×10^{15}	10^{12}	8×10^{12}	1.5×10^{11}	2.3×10^{12}	8.5×10^{11}
Q (molecules s^{-1})	2×10^{30}	10^{29}	6×10^{27}	3×10^{27}	10^{27}	2×10^{26}
Q_B (molecules s^{-1})	1.3×10^{29}	—	7×10^{26}	2.4×10^{26}	10^{26}	—

Emission rate factors (g), scale lengths (l) and scale lengths of parent molecules (l_p) are taken from ref. 10 and refer to 1 AU and a heliocentric velocity of -24.6 km s^{-1} . $4\pi I$, band intensity; N , column density. Production rates for comet Bradfield 19791 (Q_B ; refs 11, 12) at the same heliocentric distance (0.83 AU) are shown for comparison.

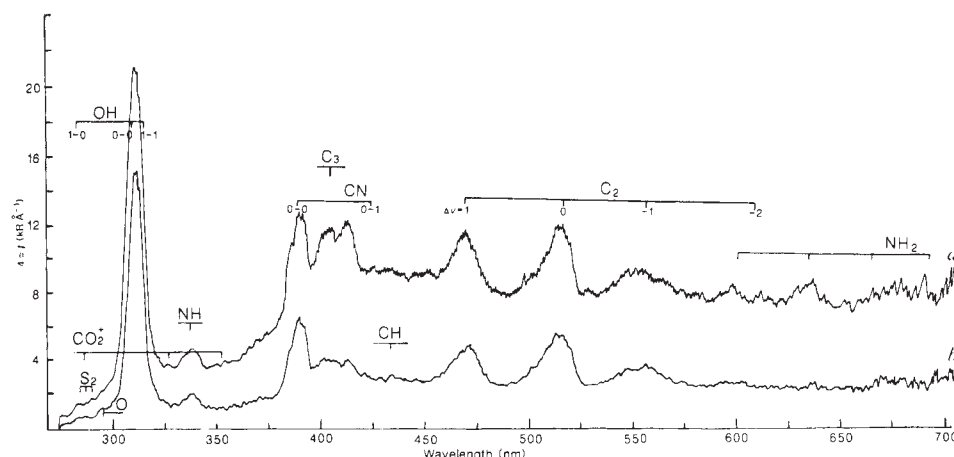


Fig. 2 Two visible spectra of comet Halley, measured at distances from the optical axis to the nucleus of $\sim 1,000$ (a) and $\sim 4,000$ (b) km.

that water is the main volatile, only indirect and sometimes ambiguous evidence in favour of water has been found; indeed, some facts appear to contradict this hypothesis^{5,6}. The $1.38\text{-}\mu\text{m}$ band present in the measured spectrum has an intensity of 0.4 MR and represents the $101 \rightarrow 000$ vibrational transition, with the same upper state also giving rise to the bands $101 \rightarrow 001$ and $101 \rightarrow 100$. Calculation based on the data of ref. 7 gives the $1.38\text{-}\mu\text{m}$ emission rate factor $g = 8.4 \times 10^{-6} \text{ s}^{-1}$ at 1 AU; that is, the water column density is $3.5 \times 10^{16} \text{ molecules cm}^{-2}$ along the optical axis and the total water production rate is $Q_{\text{H}_2\text{O}} = 4 \times 10^{29} \text{ molecules s}^{-1}$.

The most prominent features of the long-wavelength part of the spectrum are the bands of the OH vibrational-rotational system. Transitions with $\Delta v = 2$ (where v is the vibrational quantum number) dominate here. Comparison with the terrestrial night airglow spectrum measured with similar resolution⁸ demonstrates good coincidence for Q-branches only. This is

indicative of a very high rotational temperature, at which R- and P-branches become very broad and overlap. One process which can produce OH with high vibrational and rotational excitation is photolysis of a parent molecule. Vibrational levels up to the OH dissociation limit, $v = 13$, can be populated by this mechanism. The $\Delta v = 2$ sequence is the most intense and should contribute $\sim 60\%$ of the total system intensity of 9 MR. Each dissociation generates, on average, 4–5 photons, and if H_2O is the parent molecule we obtain $g = 4.5 \times 10^{-5} \text{ s}^{-1}$ at 1 AU, which gives $Q_{\text{H}_2\text{O}} = 1.7 \times 10^{30} \text{ molecules s}^{-1}$.

The spectrum in the interval $1.14\text{--}1.25 \mu\text{m}$ is measured twice at different parts of the circular variable filter, and the difference of the data is a measure of the experimental error (see Fig. 1). Many features in the spectrum exceed this difference and may therefore be real. Some of them coincide with the positions of known bands: one example is the $1.1\text{-}\mu\text{m}$ CN (0,0) transition. A full analysis of this problem will be made in the future.

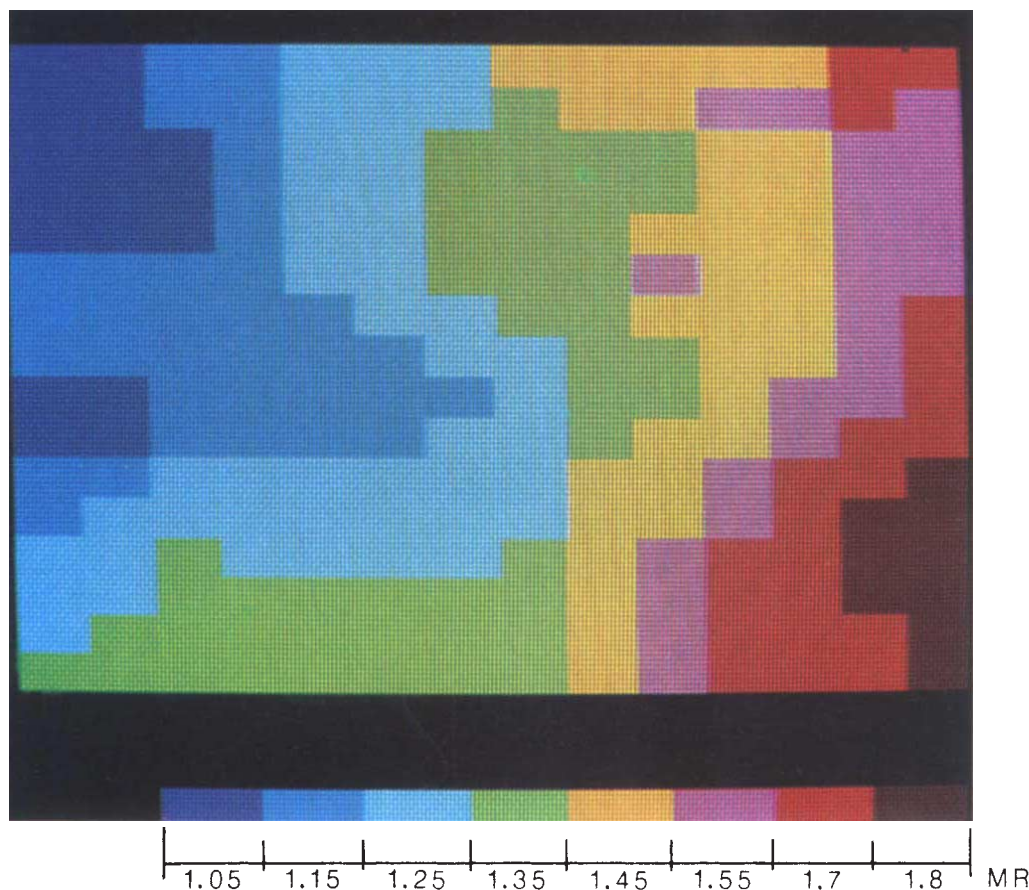


Fig. 3 False-colour image of comet Halley in the OH 309-nm band, taken at a distance of 180,000 km from the nucleus. Intensity scale is given below. The spectra in Fig. 2 refer to the lower right-hand corner (a), which is $\sim 1,000$ km from the nucleus, and to the centre (b) of the image. The image size is $6,400 \times 4,800 \text{ km}$. This image is corrected for the change of the spacecraft position during the observation, and for other sources of error.

Figure 2 shows two of the near-ultraviolet and visible (275–715 nm) spectra, with some emission bands identified. The more intense of these two spectra is weaker than the most intense spectra (measured closest to the nucleus) by factors of 10, 5 and 2.5 when comparing continuum radiation, C₂ bands and OH bands, respectively. The increase of the continuum is due to the higher dust density near the nucleus; that of the bands is caused by dissociative excitation of parent molecules (for example, the increase of the OH 309-nm band seems to be in accord with the cometary model presented in ref. 9). The interpretation of the lower spectrum (b) in Fig. 2 is given in Table 1. The ratios of the production rates of C₂, C₃ and CN to that of OH are close to those of comet Bradfield 19791, although the rates themselves appear to be an order of magnitude greater.

The OH production rate of $\sim 2 \times 10^{30}$ molecules s⁻¹ derived from the vibrational-rotational bands (above) and from the 309-nm band (Table 1) contrasts strongly with the water vapour production rate of 4×10^{29} molecules s⁻¹ obtained from the H₂O

1.38- μ m band. This problem needs further analysis and may indicate the existence of parents of OH other than H₂O.

Figure 3 is a false-colour image of the comet in the OH 309-nm band, showing the very irregular structure of the coma, with jets and clouds of dust and gas which will be studied in future.

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Near-ultraviolet and visible spectrophotometry of comet Halley from Vega 2

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We report results obtained by the near-ultraviolet and visible channel (V) of the TKS instrument¹ carried by Vega 2 during the hour preceding its closest approach to comet Halley. The brightness of the OH (0, 0) band is found to be 1.2, 1.4 and 1.8 MR (megarayleigh; $1 \text{ R} = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1} (4\pi \text{ sr})^{-1}$) at distances of 4,900, 2,450 and <1,000 km from the nucleus. The OH gas production rate is estimated to have been $\sim 9 \times 10^{29}$ molecules s⁻¹ on 9 March 1986. Modifications in the structure of the OH and CN bands observed as the distance from the line of sight to the nucleus decreases probably reflect the change in the vibration-rotation line intensity distribution of the radicals, due to the presence of radicals created in an excited state by the photolysis of their parent molecules.

The tracking accuracy of the Vega spacecraft platform provided a unique opportunity to conduct a detailed spectrophotometric study of the optical emissions originating from the inner coma of comet Halley. The secondary mirror of the TKS instrument was allowed to rotate around two perpendicular axes in order to measure the spatial distribution of the emissions. In mode A, the instrument explored a $2^\circ \times 1^\circ 30'$ field of view composed of 7 lines scanned at 15 equally spaced positions. In mode B, only the central line was scanned in a see-saw motion covering 2° . The instrument first sent cometary spectra during 12 min on 8 March when the spacecraft was at a distance of 6.8×10^6 km from the nucleus. During the encounter on 9 March, it transmitted data from 04:22 UT until the time of closest approach (07:20 UT). Observations were then made during a 3-h period on each of the next two days.

The spectral range of the V channel extends from 272 to 715 nm; the spectral dispersion is nearly linear. The instrument response measured before spacecraft launch was 4.4 pixels at half-height, or 2.7 nm. The slit width is 0.050 mm (2 pixels) and the slit length is 2.5 mm; this yields an instrument field of view of $25 \times 0.5^\circ$.

During the four observational sequences, 3,600 spectra were collected; the preliminary results presented here were obtained during the hour preceding closest approach. The three spectra shown in Fig. 1 were recorded 43 min before closest approach, at which time the distance to the nucleus was 196,000 km, and the field of view projected to this distance was $1,427 \times 29$ km. An angular distance of 2° was scanned by the secondary mirror in 15 steps, so that the linear distance between two successive steps was 489 km. Thus, in Fig. 1, spectra a, b and c correspond to distances between the spectrometer optical axis (line of sight) and the nucleus of $\sim 4,900$, 2,450 and <400 km from the nucleus. More precise location of the instrument field of view with respect to the nucleus will be achieved in future by using the platform attitude data and photometric comparisons with television images.

To evaluate the intensity of the observed emissions, a calibration curve has been drawn in Fig. 1 from laboratory measurements conducted with mercury and zinc lamps in the summer of 1984. This curve takes into account the sensitivity decrease (by a factor of 1.6) which was measured in a calibration session in June 1985 (Vega fly-by of Venus).

In the spectra shown in Fig. 1, the emission from dust (the continuum) is as intense as that of the gases. The most prominent emissions are the usual ones; that is, OH, NH, CN, C₃, CH, C₂ and NH₂. The examination of the three spectra reveals a continuous distortion due to the progressive enhancement, as the line of sight approaches the nucleus region (from a to c), of spectral signatures which are of limited spatial extent. This evolution may be clearly seen at wavelengths between 395 and 415 nm, where the bands of C₃ become clearly distinguishable. Various NH₂ bands are observed, superimposed on the C₂ ($\Delta v = 0, \pm 1, \pm 2$) bands (where v is the vibrational quantum number). The strong enhancement in spectrum c of the C₂ ($\Delta v = 0$) bands near 510 nm indicates either the presence of an as yet unidentified feature or, more likely, a strong contribution from the NH₂ (0, 12, 0) band.

In the near-ultraviolet, the brightness of the OH ($\Delta v = 0$) bands can be estimated as 1.2 MR at 4,900 km from the nucleus (Fig. 1a), 1.4 MR at 2,450 km (Fig. 1b) and 1.8 MR at 400 km (Fig. 1c); the last value is valid for all distances $\leq 1,000$ km. Due to the spectral width of the instrument, the OH (1, 1) band is superimposed on the long-wavelength wing of the (0, 0) band. The evolution of the OH bands' intensity as the inner coma is

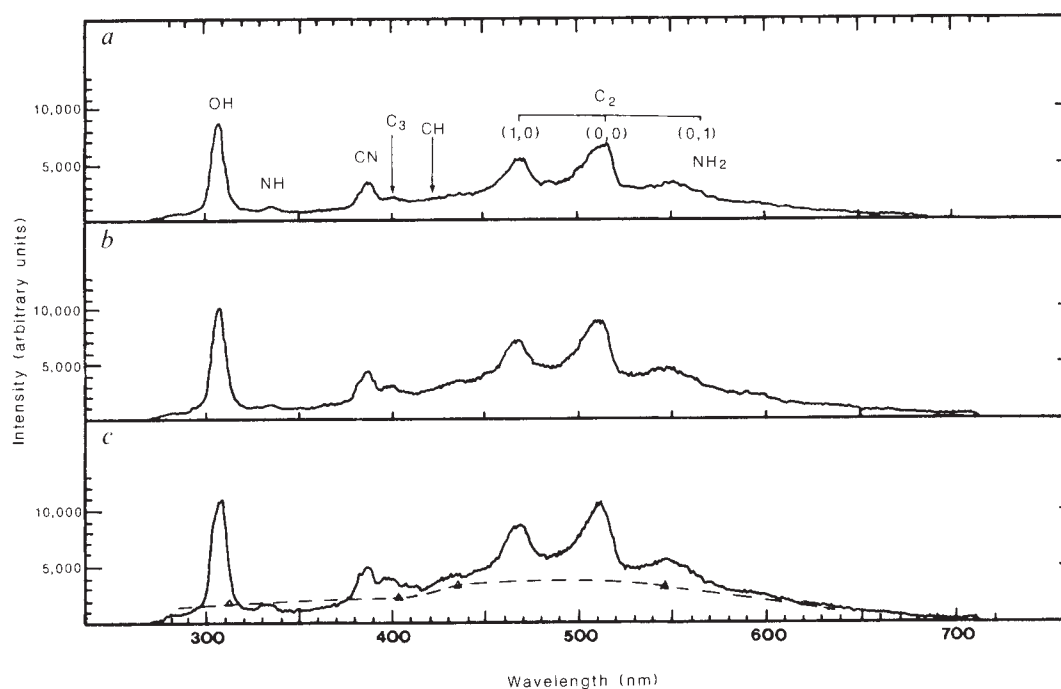
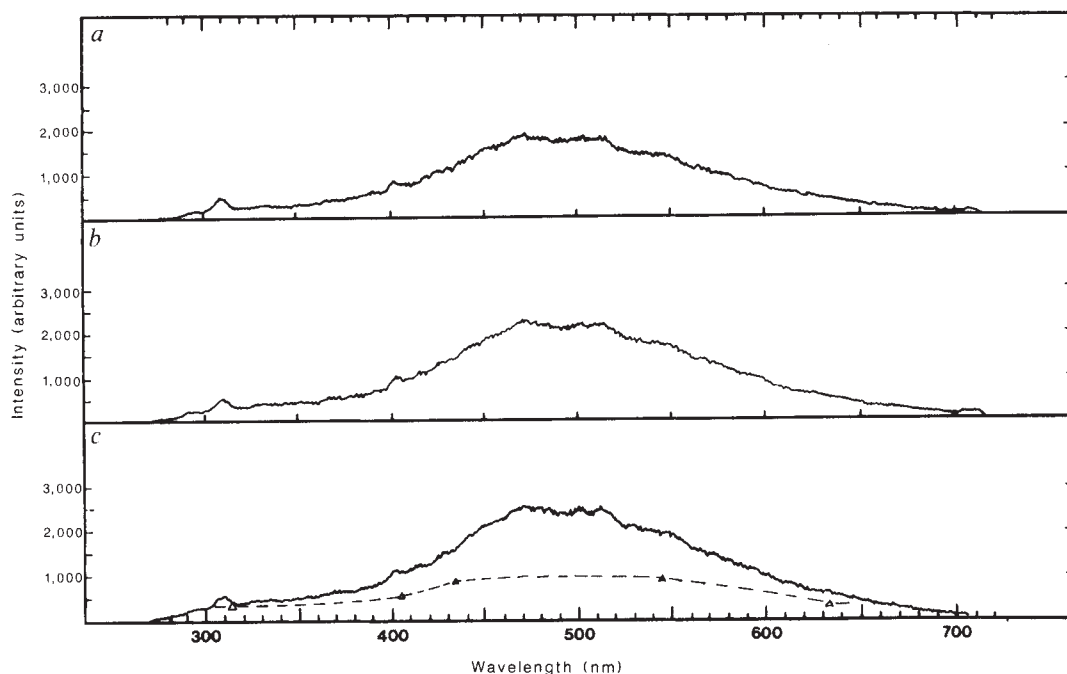


Fig. 1 Spectra obtained 43 min before closest approach, when Vega 2 was at a distance of 196,000 km from the nucleus. The field of view determined by the slit is $1,427 \times 29$ km. Spectra *a*, *b* and *c* correspond to distances of 4,900, 2,450 and 400 km between the spectrometer optical axis and the nucleus. Dashed line, calibration curve, corresponding to $30,000 \text{ R nm}^{-1}$. The triangles indicate the wavelengths of the Hg and Zn lines used for the calibration. (Units of vertical scale are digits, mode A G3.)

Fig. 2 Spectra obtained ~ 1 min before closest approach, when Vega 2 was at a distance of 12,000 km from the nucleus. Field of view determined by the slit, 88×1.7 km. Spectrum *c* corresponds to a distance of 60 km between the optical axis and the nucleus; *a* and *b* refer to points on the opposite side of the nucleus, at distances of 210 and 60 km. Dashed line, calibration curve, corresponding to $300,000 \text{ R nm}^{-1}$. (Units of vertical scale are digits, mode B G2.)



approached is characterized by a width increase and a modification of the band profile. The asymmetry seen on the short-wavelength side may indicate that a new feature exists there. Such a distortion also appears in the case of the CN (0, 0) band at 388 nm. A discrete feature appears at $\sim 382 \pm 1$ nm, and its intensity increases towards the inner coma. This feature has not been observed before², and its identification will require some additional data processing. The widening of the bands probably results from an abnormal distribution among the rotational lines of the radicals due to the fact that some of them are created (by photodissociation of their parent molecules) in the upper state of the observed transition. Jackson³ has reported the detection of newly produced excited CN radicals in cometary spectra, and has inferred the nature of their parent from the study of the rotational distribution of the CN (0, 0) violet band.

Less intense emissions are also present in the spectrum, the identification of which will require a careful subtraction of the

continuum. For instance, a feature that is present, with variable intensity, in many Vega spectra between 280 and 300 nm can probably be attributed to the S_2 molecule, as already observed by A'Hearn *et al.*⁴ in comet IRAS-Araki-Alcock. The OH emission in spectrum 1*a* is mostly due to fluorescence and leads to an estimate for the OH production rate (from a vectorial model⁵) of $\sim 9 \times 10^{29} \text{ molecules s}^{-1}$.

Figure 2 shows spectra obtained between 1 and 2 min before closest approach. The field of view determined by the slit was then 88×1.7 km. Spectrum 2*c* corresponds to a point ~ 60 km away from the maximum in the continuum emission; spectra *a* and *b* correspond to positions on the other side of the nucleus, ~ 210 and 60 km away from that maximum.

The calibration curve is plotted again in Fig. 2. Most of the gaseous components identified in Fig. 1 are still present: C_2 , C_3 , CN, NH_2 and OH. The intensity of the OH bands is $\sim 1.8 \text{ MR}$; $\sim 30\%$ of this emission is due to freshly produced excited OH

radicals. In spectra *b* and *c*, obtained at two positions located symmetrically with respect to the maximum in continuum emission, two discrete features appear near 500 nm, on the short-wavelength side of the C_2 ($\Delta v=0$) bands. These are believed to be due to the NH_2 (0, 13, 0) band; the distortion of the C_2 ($\Delta v=-1$) bands probably results from a strong contamination by the NH_2 (0, 10, 0) band. The exceptional strength of the NH_2 bands compared with other features indicates that either we are observing NH_2 radicals which have a very short-lived parent or, as in the case of both OH and CN, some of the NH_2 radicals are produced in the upper state, leading to the production of the ammonia bands.

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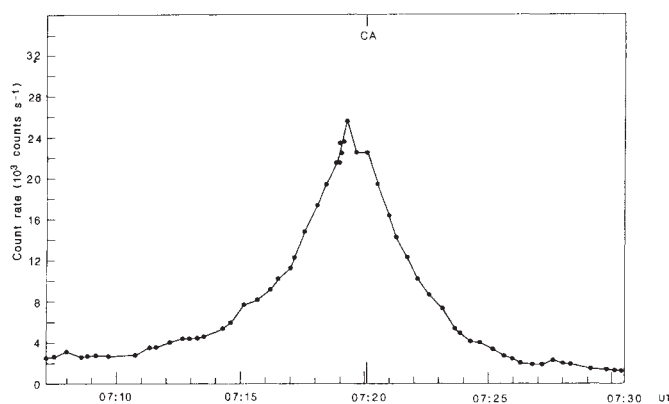


Fig. 1 Total count rate of Vega 1 FIS sensor versus time on 6 March 1986. Closest approach to the comet (CA) was at 07:20:06 UT; count rate is proportional to total gas density.

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Neutral gas measurements of comet Halley from Vega 1

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The neutral gas experiment (ING) aboard the Vega 1 spacecraft detected cometary gas within a distance of 60,000 km from the nucleus of comet Halley. A preliminary inspection of the data permits an analysis of the variation in neutral gas density. Fine structure was detected in the spatial distribution of lower-mass species.

The ING instrument comprises two independent gas detection systems, pointed in the direction of the spacecraft–comet relative velocity¹. We report here results obtained by the field ionization system (FIS), which uses a high-gradient electric field to ionize incoming atoms or molecules, while preserving their identity. After ionization these particles are accelerated to 50 keV and their respective masses determined by measuring their flight time over a distance of 7 cm, with a resolution of ~ 1 ns. The flight time t_f is related to the particle mass M through the equation $M = Kt_f^2$. The instrumental constant K is slightly mass-dependent due to the energy which particles lose in the thin carbon foil which they have to traverse in order to enter

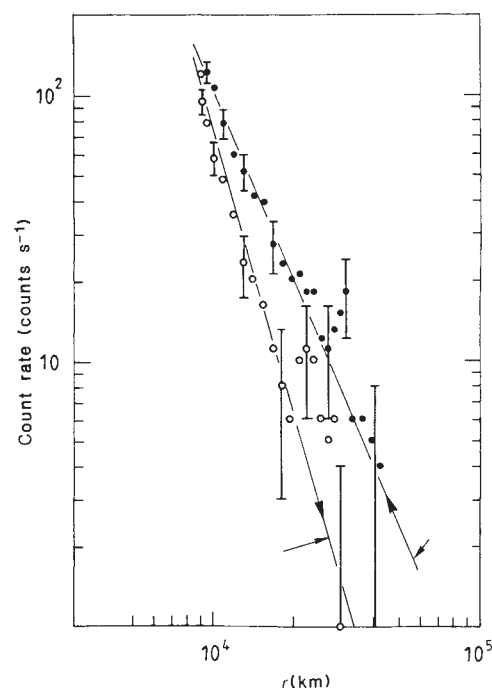


Fig. 2 Count rate versus distance r from the comet nucleus for one FIS channel, relatively assigned to mass $M = 32$. The count rate is proportional to gas density. Dots, inbound leg; circles, outbound leg; arrows show the direction of time. Closest approach to the nucleus was at 8,890 km. The data are fitted to two power laws of the form $r^{-\alpha}$: for the inbound leg, $\alpha = 2.3$, and for the outbound leg, $\alpha = 3.5$. Error bars show 1σ confidence limits.

the time-of-flight device. As energy straggling increases with mass, the resolution decreases with increasing mass. On the other hand, ionization is only slightly dependent on the incident gas velocity; thus, particles detected by the FIS sensor could originate from the spacecraft environment as well as from cometary gas. In order to minimize the background from such locally produced gas, the instrument was mounted on the top of the spacecraft, viewing the comet at an angle of 52° to the Sun–spacecraft direction. It is inclined to the ecliptic plane by 7° . The aperture field of view is $1^\circ \times 2^\circ$; an exit port makes the instrument a ‘fly through’ design. Field ionization is achieved near the surface of 40 needles, the tips of which have radii of curvature of $\sim 0.1 \mu\text{m}$. The overall sensitivity of the FIS (defined as the count rate per unit incident flux) is $\sigma_{\text{eff}} = 10^{-10}$. This, however, is a preliminary value.

During flight the Vega 1 instrument performed much as expected. The instruments started to record rates larger than background at a distance of $\sim 60,000$ km from the cometary nucleus and before the onset of large dust fluxes. Figure 1 shows the total count rate of the FIS sensor as a function of time. This rate is the sum of all counts recorded by the instrument, and thus the sum of all possible contributions by cometary neutrals to the rates.

Figure 2 shows count rates for a single channel, plotted as a function of radial distance r from the cometary nucleus. The data have been fitted to a power-law dependence $r^{-\alpha}$ for both the inbound (dots) and outbound (circles) legs. For the inbound portion we find roughly an r^{-2} dependence, whereas for the outbound leg $\alpha \approx 3.5$. For the density $n(r)$ of cometary neutrals, model calculations² provide a dependence $n(r) \approx r^{-2} \exp(-r/ur)$. For distances $r \ll 10^6$ km, $n(r) \approx r^{-2}$ is in agreement with our inbound observations. The steeper slopes observed outbound might be due to the highly variable, non-spherically-symmetric expansion of the cometary atmosphere during that time, or to a finite region of enhanced outflow in conjunction with jets, entered after closest approach.

In our low-mass channels on the outbound leg, we observe spikes superimposed on the general trend. These spikes were not observed in channels corresponding to higher mass numbers.

The spikes have typical durations of up to 10 s, implying high-density structures with dimensions of ~ 500 – 700 km. The widths of these structures resemble those which have been observed by the DUCMA dust experiment on Vega 1 (ref. 3). The time-resolution of our instrument is 2 s, implying that structures of dimensions larger than 150 km can be readily identified. This is of great interest, as a series of prominent spikes appeared over a 200-s period at a distance of 4.5×10^4 km from the nucleus on the outbound leg.

Because the FIS sensor is of a new design, being applied in spaceflight for the first time, the evaluation of the instrument's performance will require further data analysis and calibration.

We thank many people from the Max-Planck-Institut für Aeronomie and the University of Arizona for help in building, testing and calibrating the instrument, and in particular, R. Z. Sagdeev, K. I. Gringauz, W. I. Axford, V. M. Vasyliunas and K. Szegő. The participation of the University of Arizona in this project is partially funded by NASA contract NASW 3627 and NSF grant INT-8205325.

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Dust coma structure of comet Halley from SP-1 detector measurements

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The SP-1 detectors aboard the Vega 1 and Vega 2 spacecraft measured the spectral and spatial distributions of dust grains, with the aim of investigating the dust release process and other properties of the comet nucleus^{1–3}. The dust particle mass spectra do not exhibit the expected low-mass cutoff⁴ at 10^{-14} g; instead, they continue to rise to $\sim 10^{-16}$ g. The apex of the dust paraboloid resulting from scattering of sunlight is estimated to lie at a distance of 40 – 45×10^3 km from the nucleus, although there is a small number density of particles well beyond this boundary. Particles of mass 10^{-12} – 10^{-14} g are relatively depleted at large distances from the nucleus, due to stronger light scattering by these particles. Strong inhomogeneity of the dust number density suggests the existence of a sunward-pointing cone of enhanced dust emission, of width 70 – 80° . The spatial dispersion of a narrow dust jet has been used to estimate the sense and period of rotation of the nucleus and the approximate azimuthal location of the jet source, as well as the mass-dependent velocity dispersion of the dust particles.

Each dust particle that hits the solid target of the SP-1 detector gives rise to a charged plasma cloud⁵; the amplitude of each charge pulse is measured and recorded by decade counters. A preliminary estimate for the mass range Δm_n of the n th channel is obtained by using an empirical conversion factor⁶, $\approx 10^3$ C g⁻¹; thus, Δm_n is 10^{-n-9} to 10^{-n-10} g for $n = 1$ to 6, and Δm_7 is 10^{-16} to 3×10^{-17} g. The sensitive area of the detector is 81 cm² and the sampling rate is 0.5 Hz. For a detailed description of the instrument, see ref. 7.

The SP-1 data reported here were obtained on Vega 2 on 9 March 1986. Vega 1 recorded higher number fluxes at closest approach, and a slightly different spatial distribution.

The scattering of sunlight forces cometary dust particles away from the Sun, so that their trajectories lie within a 'dust paraboloid'⁸, with its focus at the comet nucleus. The dust number density should decrease as R^{-2} , where R is the distance from the nucleus, although deviations from the R^{-2} law will be observed closer to the paraboloid and within dust jets. To reveal the large-scale structure of the dust coma we have normalized the measured count rate by a factor $(R_0/R)^2$, where R_0 is the distance of closest approach (8,030 km).

Figure 1 shows that the dust coma is quite inhomogeneous; nevertheless, the profiles in different mass ranges show similar features. We have identified several boundaries (vertical lines in Fig. 1), separating regions of differing dust characteristics. The outermost boundaries (a and e in Fig. 1) are believed to be those of the dust paraboloid, which must therefore have its apex at 40 – 45×10^3 km (curve f in Fig. 1). A lower but significant dust number density was observed well beyond these boundaries (the first particle was recorded at a distance of 3.2×10^5 km from the nucleus); this may be the result of velocity dispersion.

The most striking large-scale feature in the SP-1 data from both Vega 1 and Vega 2 is the region of strong, narrow jets contained within a cone of width 70 – 80° , oriented approximately towards the Sun (boundaries c and d in Fig. 1). This cone of dust ejection is easily seen in television images taken from both Vega spacecraft at distances of several hundred kilometres⁹; these images also show the cone angle to be $\sim 75^\circ$ (Fig. 1). If we assume that the most pronounced jet examined (with external boundary b in Fig. 1) is reflected from the calculated paraboloid, then it may originate from the edge of the active cone. We believe that a sunward-pointing cone of dust ejection, with relatively sharp boundaries, is an important and long-lived feature of the dust emission of comet Halley (it could also be seen in images taken from the Giotto spacecraft).

One of the jets in the sunward-pointing dust cone exhibited mass dispersion along the spacecraft path; that is, heavier particles were observed before lighter ones (Fig. 2a). As shown in Fig. 2b, this may reflect the traversal by the spacecraft of a very narrow jet (not necessarily continuous), emitted by a rotating nucleus. If we assume velocities v_1 and v_2 for the particles

Fig. 1 SP-1 count rates (counts cm^{-2} per 2 s) in different mass ranges (channels 1–6), plotted along the Vega 2 trajectory (shown below ('V2'), projected on the plane containing the spacecraft trajectory, with the x and y axes pointing, respectively, towards the Sun and eastwards). The data from channel 7 need additional processing due to the overload of collectors by plasma at closest approach. For channel n , the approximate mass range is 10^{-n-9} to 10^{-n-10} g. The count rates have been normalized by a factor $(R_0/R)^2$, to remove the underlying trend. For ease of display, the data from each channel have been displaced by one order of magnitude along the ordinate. Vertical lines mark boundaries referred to in the text: a, e , boundaries of the dust paraboloid; b , most pronounced dust jet; c, d , boundaries of the sunward-pointing active cone. Curve f is the projection of the paraboloid fitted to boundaries a and e , and lines g and h mark the boundaries of the active cone (corresponding to c and d); the comet's position and orientation are indicated by a television picture⁹ taken from Vega 2. Letters A to F refer to the times for which mass spectra are shown in Fig. 3. The lower horizontal axis is distance of the spacecraft from closest approach (km); the upper horizontal axis is Universal Time (UT) on 9 March 1986.

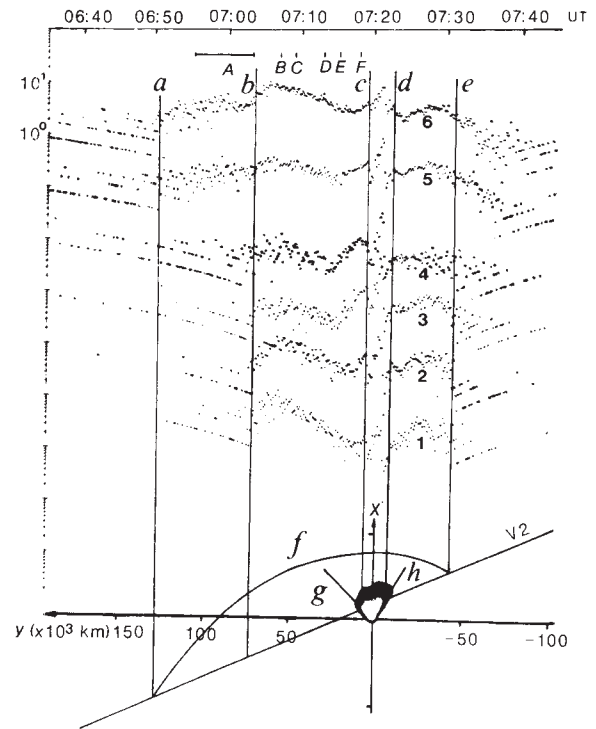
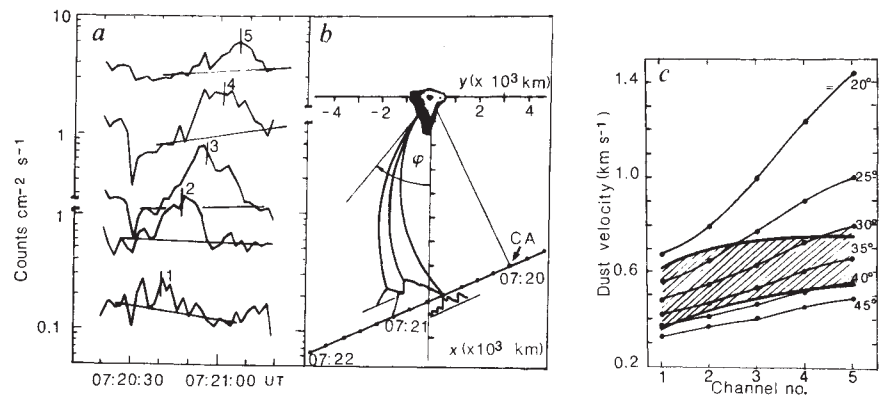


Fig. 2 *a*, Count rate in channels 1–5 plotted against Universal Time, for a short interval following closest approach. The channel 6 count rate showed no increase at this time. Note that a segment of the vertical axis is repeated, to prevent overlap of the data. (Curves 1–3 refer to lower scale, 4 and 5 to upper scale.) The straight sloping lines indicate the background level. The geometry of the observations is shown in *b* (projection on the plane containing the spacecraft trajectory; x and y axes as in Fig. 1, with scale in km): the spacecraft trajectory is shown in relation to a television image⁹ obtained near closest approach, showing the comet nucleus and jets. For comparison with *a*, the trajectory is marked at 10-s intervals of Universal Time; the point of closest approach is also indicated (CA). Portions of the count rate data from channels 1, 3 and 5 are plotted along the trajectory, to illustrate how the displacement of the peaks in time may result from traversal of a rotating dispersed jet (see text for details). The angle ϕ is the azimuthal location of the jet source at the time of closest approach. In *c*, velocity dispersion curves calculated for different values of ϕ are compared with the region (hatched) occupied by theoretical dispersion profiles^{10,11} for gas terminal velocities of 580–650 m s^{-1} . The best fit is obtained for $\phi = 35 \pm 5^\circ$.



recorded by channels 1 and 5, respectively, we can obtain the rotation period, T , of the comet nucleus from the expression

$$T = 2\pi \left(\frac{r_1 - r_5}{v_1 - v_5} \right) / (\phi_5 - \phi_1),$$

where (r_n, ϕ_n) are the polar coordinates of the point at which the maximum count rate was observed in channel n (see Fig. 2*b*). With estimates^{10,11} of 350 and 500 m s^{-1} for v_1 and v_5 , we obtain $T \approx 50$ h, and a clockwise sense of rotation, as seen from above the ecliptic. This is consistent with astronomical observations¹² and with Vega 1 and Vega 2 television images⁹.

Alternatively, if we take the rotation period derived from optical data^{9,12}, $T \approx 52$ h, we can calculate the velocity dispersion necessary to explain the observed mass dispersion, for different azimuthal locations of the jet source (Fig. 2*c*). Comparing the calculated dispersion curves with the region occupied by theoretical dispersion profiles^{10,11} for gas terminal velocities of 580–650 m s^{-1} (hatched area in Fig. 2*c*), we obtain a best-fit estimate, $\phi = 35 \pm 5^\circ$, for the azimuth of the source at the time

of the Vega 2 closest approach. The angular width of the jet at $\sim 9,000$ km from the nucleus was $\sim 10^\circ$; narrow jets can also be seen in Vega 2 television images taken from near the point of closest approach⁹.

Figure 3 shows the dust particle mass spectra obtained for the six time intervals (A–F) shown in Fig. 1. The most striking feature is the large number of low-mass particles (high channel number): the mass spectra continue to rise to $\sim 10^{-16}$ g. If the mass distribution is approximated by a power law, $n(m) \propto m^{-\alpha}$, we obtain a mass distribution index $\alpha \approx 1.25 \pm 0.05$ for $m < 10^{-12}$ g, and $\alpha \approx 1.50 \pm 0.05$ for $10^{-12} < m < 10^{-10}$ g; these spectra are thus flatter than those obtained from photometric data¹³.

Another important feature of the mass spectra is the gradual decrease in number of particles of mass 10^{-12} – 10^{-14} g with increasing distance from the comet nucleus (Fig. 3). This effect is probably caused by the larger influence of solar light pressure on particles in this mass range (Mie resonances)^{13,14}.

The dust production rate in the mass range $m \leq 10^{-10}$ g has been estimated from our Vega 2 measurements to be $\sim 300 \text{ kg s}^{-1}$.

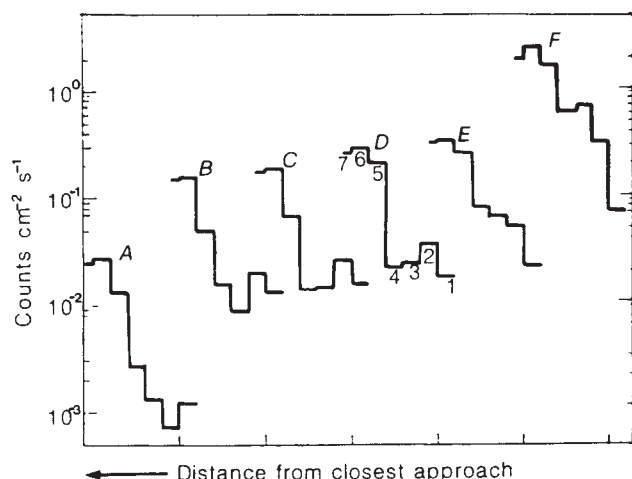


Fig. 3 Time-averaged mass distributions obtained during the intervals A–F shown in Fig. 1 (A, 9-min average; B–F, 10-s averages). Note the large number of low-mass particles (high channel number), and the gradual decrease in number of particles in channels 3 and 4 (10^{-12} – 10^{-14} g) with increasing distance from the comet nucleus.

If we assume that the relationship between the increase in spectral slope observed between channels 2 and 1 and that observed between channels 3 and 2 continues in subsequent (larger) mass ranges, we obtain a mass output with a maximum

in some mass range decade (out of our range), which makes an upper limit of integration unnecessary. We thus obtain a rough estimate of $\sim 4,000 \text{ kg s}^{-1}$ for the total dust production rate on 9 March 1986.

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Comet Halley dust environment from SP-2 detector measurements

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The SP-2 experiment carried by the Vega spacecraft during their encounter with comet Halley was designed to determine the spatial distribution of cometary dust particles and their mass distribution over the range $\sim 10^{-16}$ – 10^{-6} g. The first infrequent dust particle impacts recorded by the SP-2 sensors indicated that Vega 1 entered the cometary dust coma at a distance of $\sim 280,000$ km from the nucleus. Although the subsequent rapid and even spectacular developments were not unexpected and the results of the *in situ* measurements agree well with the general predictions of cometary dust environment models^{1,2}, a number of remarkable features were revealed, such as the high density of sub-micrometre-sized particles, considerable variations in the particle mass distribution observed in different regions of the coma and particularly in jets, and the asymmetry relative to the comet–Sun line.

The techniques used evolved from the near-Earth cosmic dust studies carried out on Kosmos satellites from 1966 to 1972³. The SP-2 experiment⁴ comprises two types of particle impact sensor: an acoustic sensor and an ionization (plasma) sensor.

The acoustic sensor consists of a thin circular plate of surface area $S = 500 \text{ cm}^2$ bearing three piezoelectric transducers which detect the elastic deformation waves generated in the plate by the incident particle. The response signal of such a detector is proportional to the total momentum transferred to the plate during the particle impact, which is the sum of the incident

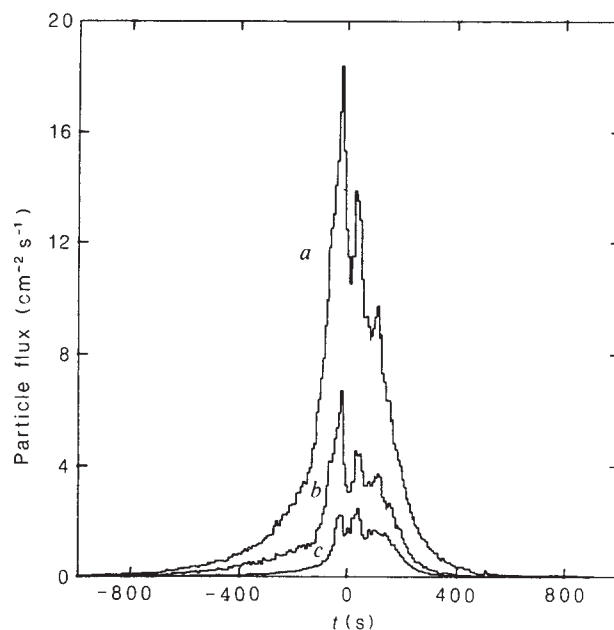


Fig. 1 Dust particle flux distribution $N(>m_i, t)$ along the Vega 1 trajectory. a, $m > 10^{-15}$ g; b, $m > 10^{-13}$ g (a and b, impact plasma sensor data); c, $m > 10^{-11}$ g (acoustic sensor data).

particle momentum and the momentum of ejecta. Taking this into account, the instrument sensitivity threshold $P_{\min} = 2.5 \times 10^{-5} \text{ dyn s}$ corresponds to a cometary dust particle mass $m_{\min} \approx 3 \times 10^{-13} \text{ g}$. The particle mass range 3×10^{-13} – $2 \times 10^{-6} \text{ g}$ is divided uniformly into 16 logarithmically spaced channels with a step size $\Delta m/m = 2.82$.

The plasma sensor comprises a chamber with a target of area 40 cm^2 and an electrode system which separates the electrons and ions from the plasma cloud produced by the particle impact

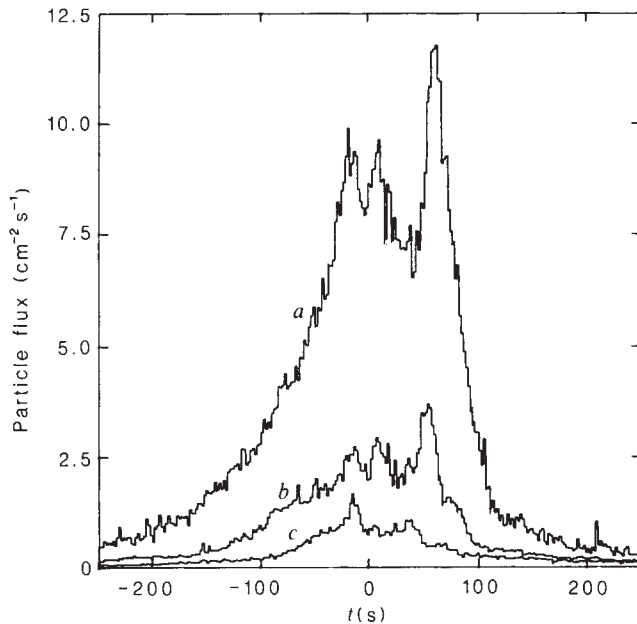


Fig. 2 Dust particle flux distribution $N(>m_i, t)$, along the Vega 2 trajectory. *a*, $m > 10^{-15}$ g (impact plasma sensor data); *b*, $m > 10^{-13}$ g; *c*, $m > 10^{-11}$ g (*b* and *c*, acoustic sensor data).

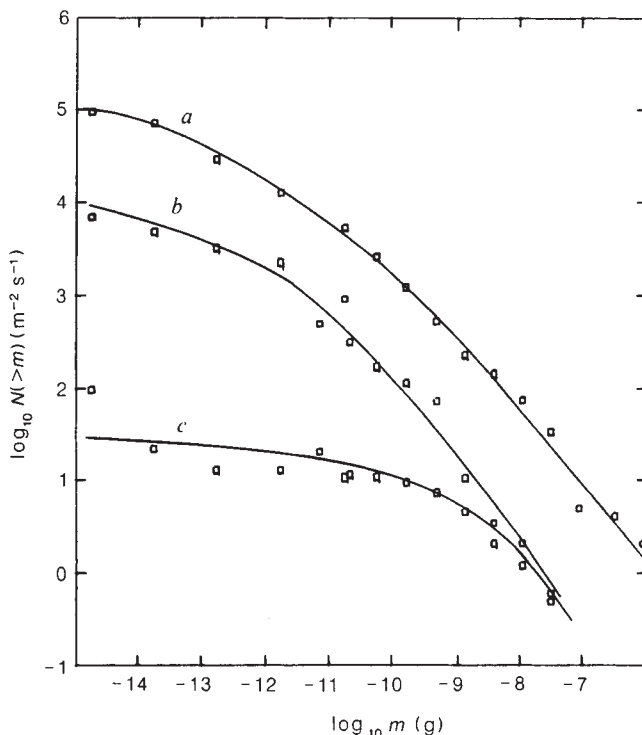


Fig. 3 Dust particle mass distributions $N(>m)$ for three regions of the Vega 1 trajectory. *a*, $t = -80$ s, accumulation time 2 s; *b*, $t = -8$ min, accumulation time 100 s; *c*, $t = -(45-25)$ min, accumulation time 20 min. Curves are preliminary best-fit lines to the experimental points.

and measures the collected negative charge. This sensor detects dust particles in the mass range $\sim 10^{-16}$ – 10^{-11} g and has six integral channels with $\Delta m/m \approx 10$. Thus the mass distribution measurements of the two sensors cover the range $\sim 10^{-16}$ – 10^{-6} g. The spectrum accumulation time is 1 s; all the sensor and measurement systems of the instrument are duplicated.

Figure 1 shows dust particle fluxes, $N(>m_i)$ measured by Vega 1, as a function of time relative to the time of closest

approach to the comet nucleus. The dust flux detected is $N(>m_i) = n(>m_i)v$, where $n(>m_i)$ is the spatial density of dust particles of mass greater than m_i , and v is the spacecraft velocity with respect to the comet. The simplest approximation is $n(>m_i, R) \propto R^{-2}$, where $R = (R_0^2 + v^2 t^2)^{1/2}$ is the current distance of the spacecraft to the comet nucleus and R_0 is the distance of closest approach, reached at $t = 0$. Thus, we have $N(>m_i, t) = n_0(>m_i)v[1 + (t/t_0)^2]^{-1}$, where $t_0 = R_0/v$ and n_0 is the spatial density of dust particles at $t = 0$. For the Vega 1 fly-by, $v = 79.2$ km s $^{-1}$, $R_0 = 8,890$ km and $t_0 = 112$ s.

Figure 2 shows some $N(>m_i, t)$ distributions for Vega 2 ($R_0 = 8,030$ km, $v = 76.8$ km s $^{-1}$, $t_0 = 105$ s), plotted on an expanded time scale. The $N(>m_i, t)$ curves agree satisfactorily with the simplest assumption of an R^{-2} dependence of dust particle spatial density; however, the data exhibit some interesting and remarkable features.

The $N(>m_i, t)$ plots are noticeably different for different m_i , implying that the mass distributions at different distances from the nucleus may vary substantially. The distributions measured by Vega 1 and Vega 2, separated by an interval of three days, are clearly different. These differences undoubtedly reflect temporal variations and an angular asymmetry of the dust stream emanating from the nucleus. Further analysis should allow the estimation of the velocity dispersion; that is, the time taken by dust particles of different mass to reach different points along the spacecraft trajectory.

Certain pronounced features are present near closest approach ($t = 0$) in the $N(>m_i)$ distributions measured by both spacecraft, which manifest themselves differently for different values of m_i . Particularly remarkable is the strong peak near $t = 60$ s in Fig. 2, which corresponds to an intense and rather narrow dust jet. Its position on the time axis shifts continuously to the left with increasing particle mass, implying that the particle mass distribution varies considerably within a distance of only $\sim 2,500$ km along the Vega 2 trajectory. This variation is probably due to a rapid spreading of the spatial structure of the jet, caused by radiation pressure.

At $t = 251$ s the acoustic sensor of Vega 2 became damaged and stopped transmitting useful information. The impact plasma sensor of the instrument continued to function normally.

Figures 3 and 4 show some dust particle mass distributions obtained at different points along the Vega 1 and Vega 2 trajectories in the central region of the coma ($R < 25,000$ km). The spectra exhibit obvious differences. In the low-mass region, $m < 10^{-11}$ g, the slope of the distribution decreases sharply; however, we do not observe the low-mass cutoff which was predicted by some models based on photometric data⁵.

Of considerable interest is the dust particle mass spectrum obtained near the boundary of the cometary coma. Our data have not revealed any sharp boundary of the dust envelope. The first dust particle impacts were detected at a distance of $\sim 280,000$ km from the nucleus, but the count rate statistics accumulated far from the nucleus were insufficient to allow the derivation of an $N(>m)$ distribution for time intervals corresponding to $\Delta R \approx 10^3$ km. However, the impact count rate starts to increase steadily at somewhat smaller distances, ~ 1.8 – 2.0×10^5 km, from the nucleus (corresponding to $t \approx -2,500$ s). The spectra averaged over a large part of the inbound trajectory (traversed in 20 min) reveal a strong enrichment in particles of high mass (Figs 3c, 4c).

The total number of impacts detected during the encounters agrees satisfactorily with predictions, except for the data obtained for the lightest particles. For instance, for Vega 2 the fluences (per m 2) were 1.8×10^7 , 3.1×10^6 and 5.8×10^4 for particle masses greater than $\sim 10^{-15}$, 10^{-12} and 10^{-9} g, respectively. The steepness of the mass distribution in the central part of the dust coma where the bulk of the dust is confined increases with particle mass. Approximating the distribution function for particle size, a , by a power law, $n(a) \propto a^{-u}$, we derive the following estimates for u : for $10^{-16} < m < 10^{-12}$ g, $u = 1.5$ – 2.5 ;

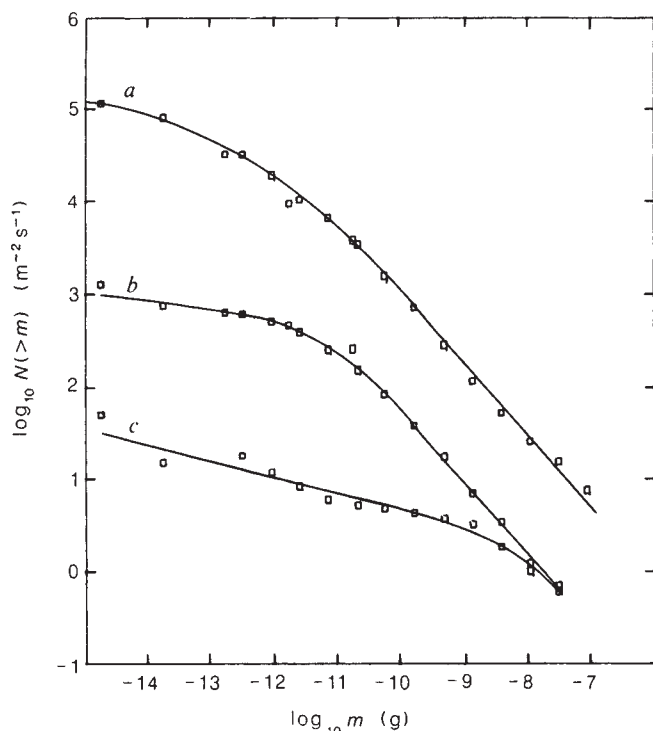


Fig. 4 Dust particle mass distributions $N(>m)$ for three regions of the Vega 2 trajectory. *a*, $t=58$ s, accumulation time 4 s; *b*, $t=-11$ min, accumulation time 100 s; *c*, $t=-(48-28)$ min, accumulation time 20 min. Curves are preliminary best-fit lines to the experimental points.

for $10^{-12} < m < 10^{-9}$ g, $u \approx 2.5-3$; and for $m > 10^{-9}$ g, $u \approx 3.4$.

Note that because u is always less than 4, integration of the distribution $M \propto \int a^{-u+3} da$ yields a divergent result for the total dust mass. However, it is natural to expect the distribution to have a cutoff corresponding to particles of mass ~ 1 g which are too massive to be carried by the gas flow away from the nucleus. If we take for the dust particle velocity $v_d \approx 10^3 (\rho a)^{-0.5} \text{ cm s}^{-1}$ (ref. 2), we find that the total dust production rate of the comet $\dot{M}_d$ is related by a simple expression to the total mass ΔM of the dust particle flux in the size interval a_0 to $a_{\max}$ detected by the instrument sensors during the encounter:

$$\dot{M}_d = \frac{2 \times 10^3}{\sqrt{\rho}} R_0 \frac{(4-u)}{(3.5-u)} \frac{a_{\max}^{3.5-u} - a_0^{3.5-u}}{a_{\max}^{4-u} - a_0^{4-u}} \Delta M$$

where $R_0 \approx 8 \times 10^6$ cm is the distance of closest approach to the nucleus and ρ is the dust particle density. For the range $1 > m > 10^{-9}$ g, $a_{\max} \approx 1$ cm, $a_0 \approx 10^{-3}$ cm, which provides the major contribution to the total dust mass, our data suggest that $\Delta M \approx 1.5 \times 10^{-6} \text{ g cm}^{-2}$. This leads to an estimate $\dot{M}_d \approx (5-10) \times 10^6 \text{ g s}^{-1}$, which agrees fairly well with the predictions of cometary dust models. By comparing this result with the gas production rate estimated from gas flux measurements⁶, $Q \approx 1.3 \times 10^{30} \text{ molecules s}^{-1}$, we conclude that comet Halley is indeed characterized by a high dust-to-gas production rate ratio, $\mu = \dot{M}_d / \dot{M}_g \approx 0.1-0.25$. The fact that the dust paraboloid does not have a sharp boundary can be accounted for by a large velocity dispersion of particles of comparable size, and by their non-sphericity and different lifetimes. Although the first particles to be detected were in the lowest detectable mass range, it is clear that in the periphery of the dust coma large particles are relatively more abundant than in the central regions (Figs 3, 4). This is most probably due to the resonant enhancement of the light-scattering cross-section for particles of size comparable with the wavelength⁷.

Within the dust coma the particle spatial distribution exhibits a complex structure. It is remarkable that the locations of the

intense peaks in the time profiles obtained from Vega 1 and Vega 2 (Figs 1, 2) agree closely, while the peak intensities differ strongly. Indeed, the first and second peaks in Fig. 1 correspond to the second and third (most intense) peaks in Fig. 2. The third peak of Vega 1 was found by Vega 2 to have diminished markedly in intensity. This pattern is undoubtedly associated with the dust jet which had been expected to exist in comet Halley. Indeed, in a photograph taken in 1910, Larson and Sekanina⁸ identified three long-lived jets with a periodicity of ~ 20 h. Further analysis of our data should permit a reliable determination of the temporal behaviour of the observed dust jets.

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Dust counter and mass analyser (DUCMA) measurements of comet Halley's coma from Vega spacecraft

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The Vega encounters with comet Halley allowed the first direct measurements of the spatial and temporal distributions of the masses and fluxes of dust particles originating from the comet nucleus. These data are fundamental for establishing the physical processes of dust emission from the nucleus, their propagation to form a coma, and the behaviour of dust jets. The measurements reported here were made with instruments employing a new principle of dust detection^{1,2}, which have a high time-resolution ($\sim 4 \mu\text{s}$) over a large range of dust fluxes and masses. The dust coma, whether quiescent (as seen by Vega 2) or containing a major jet structure (as seen by Vega 1), displays large, short-term variations throughout, which are at times quasi-periodic. The integral mass spectra increase in intensity to the lowest masses measured (contrary to some theoretical models), and the flux levels lie approximately in the ranges estimated previously from ground-based observations⁶. The coma is highly dynamical on all spatial and temporal scales, suggesting a complex structure of localized regions of dust emission from the nucleus.

The overall character of our dust measurements from the two encounters is shown in Fig. 1, in which 2-s averages of dust count rates are plotted against the time from closest approach to the nucleus by Vega 1 (*a*) and Vega 2 (*b*). These graphs display the integral count rates of all dust particles of mass $\geq 1.5 \times 10^{-13}$ g. Until the onset of the large flux shown in Fig. 1*a*, which we believe to be due to a dust jet emanating from the active side of the nucleus³ (S. Larson, personal communication),

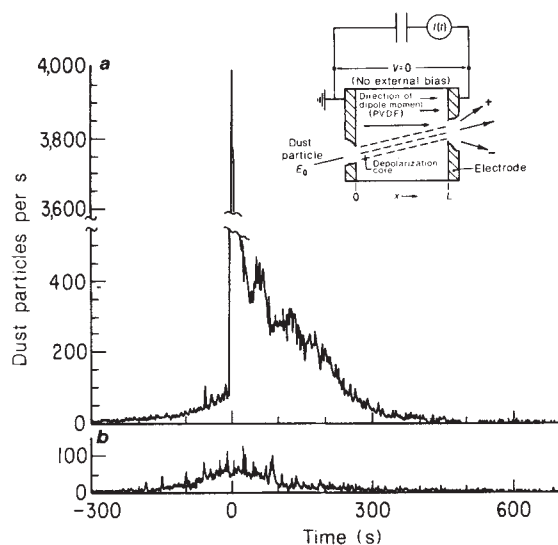


Fig. 1 Count rate of dust particles of mass $\geq 1.5 \times 10^{-13}$ g detected at Vega 1 (a) and Vega 2 (b), averaged over 2-s intervals and plotted against time from closest approach for each spacecraft ($8,890 \pm 45$ and $8,030 \pm 45$ km, respectively). The ordinate in a is interrupted to allow the peak intensity to be shown. Inset, schematic diagram illustrating the PVDF detection principle^{1,2}.

the intensities and mass distributions are remarkably similar for the two pre-closest-approach periods. Because of its rotation period of ~ 52 h (ref. 8), the nucleus was presenting a relatively inactive side towards the Sun during the Vega 2 encounter.

The DUCMA detector of area 75 cm^2 was within 10° of perpendicular to the velocity vector of the spacecraft relative to the dust. Fortunately, the detector is mounted so that it cannot 'see' possible ejecta from massive dust particles striking the solar arrays or other spacecraft structures, except for a small portion of the guard cone², used to retain the surrounding thermal blanket. A dust particle generates an electrical pulse when it enters the detector foil, composed of the polymer polyvinylidene fluoride (PVDF), the molecules of which are polarized, as shown in Fig. 1 inset. The rapid depolarization in the volume destroyed by the dust particle induces a fast (nanosecond-range) pulse with amplitude proportional to $m^a v^b$, where m and v are the mass and relative velocity of the particle, respectively. Since v is the known spacecraft velocity ($77\text{--}79 \text{ km s}^{-1}$), the mass of the particle can be determined. The pre-launch calibrations, responses and other details of the instrument have been published^{1,2}. (All count rates designated here as M1, M2, M3 and M4 correspond in the published instrument description² to M1NV, M2NV, and so on.) Because there was no laboratory dust accelerator available which could calibrate our instruments up to the spacecraft velocities, we have extrapolated our calibrations into the spacecraft velocity range. The instruments on both spacecraft performed perfectly.

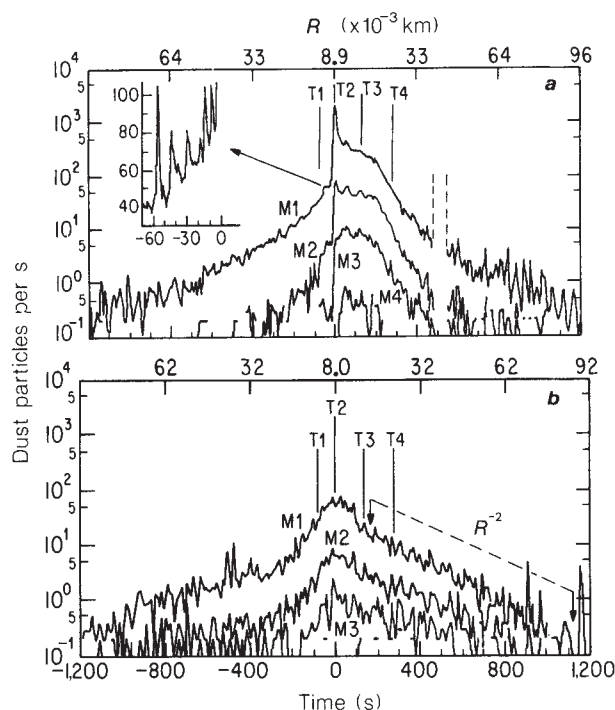


Fig. 2 Dust count rates for Vega 1 (a) and Vega 2 (b), averaged over 10-s intervals, for the four mass thresholds listed in Table 1. There was one telemetry dropout, marked by dashed lines in a. T1–T4 are times at which the mass spectra in Table 2 were derived. Also shown in b is an interval where an R^{-2} flux dependence holds for particles of mass $\geq 1.5 \times 10^{-13}$ g. On the scale of this figure the M4 event rates in b fall close to the 10^{-1} line, with only occasional values appearing above this line. Inset, detail of a portion of the M1 spectrum (time scale in seconds), showing characteristic quasi-periodic fluctuations.

Figure 2 shows in greater detail the intensity-time plots for the four mass thresholds specified in Table 1. These plots illustrate the remarkable quasi-periodic fluctuations (such as those shown in Fig. 2a inset) which are present over a wide range of flux levels. These small-scale intensity variations which correspond to spatial structures of 200–300 km are not believed to be due to any artefacts of the missions. These flux enhancements may be present over substantial periods of time, in which case they represent fast dust streams, or microjets, along a spiral that would map back to the nucleus over a rotation angle of $30\text{--}35^\circ$. The fact that, at 8,000–9,000 km from the nucleus, some of these enhancements are only 200–300 km wide suggests that the source regions on the nucleus are small and discrete. A less likely cause of the flux enhancements might be sequences of dust bursts from the nucleus. Further study of the measurements should decide this question.

By relating time of measurement to spacecraft–nucleus distance, R , we have found, for 10^{-13} g particles, that dust fluxes within extensive regions of the coma follow an R^{-2} dependence

Table 1 Peak flux (F) and number density (N) measured by DUCMA instruments

Mass threshold		M1 ($m \geq 1.5 \times 10^{-13}$ g)		M2 ($m \geq 9 \times 10^{-13}$ g)		M3 ($m \geq 9 \times 10^{-12}$ g)		M4 ($m \geq 9 \times 10^{-11}$ g)	
Averaging interval		2 s	10 s	2 s	10 s	2 s	10 s	2 s	10 s
Vega 1	F	53	25	1.7	0.9	0.1	7×10^{-2}	7×10^{-3}	1×10^{-3}
	N	7×10^{-6}	3×10^{-6}	2×10^{-7}	1×10^{-7}	2×10^{-8}	8×10^{-9}	8×10^{-10}	2×10^{-10}
Vega 2	F	—	1	—	0.1	—	3×10^{-2}	—	—
	N	—	1×10^{-7}	—	1×10^{-8}	—	4×10^{-9}	—	—

F is measured in $\text{cm}^{-2} \text{ s}^{-1}$, N in cm^{-3} .

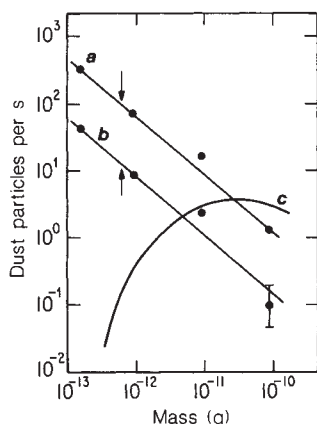


Fig. 3 Integral mass spectra derived from 2-min averages at time T3, assuming a power-law dependence, $F \propto m^{-\alpha}$. Experimental errors not shown are less than the dot diameter. The two straight lines are fits to the Vega 1 (a) and Vega 2 (b) data, with spectral index $\alpha = 0.9$. The curve c is the differential spectrum predicted by Carey and McDonnell⁵ for direct particles at 500 km, and the arrows indicate the spectral peak predicted by Divine *et al.*⁶.

(see Fig. 2b) out to distances of $\sim 100,000$ km; that is, beyond the distances predicted by some models^{4,6}.

The integral mass spectra sampled at four times by Vega 1 and Vega 2 (T1–T4, Fig. 2) have been obtained by assuming that the integral spectra in the DUCMA mass range can be represented by a power law in mass, so that the flux $F(m)$ is proportional to $m^{-\alpha}$. Values of α for each sampling time are listed in Table 2, which shows that there is a significant, progressive reduction in α at increasing (outbound) radial distances.

Table 2 Integral mass spectral index, α

Time	T1	T2	T3	T4
Vega 1	1.6	2.0	1.0	0.9
Vega 2	1.4	1.3	1.0	1.0

All values are uncertain to ± 0.1 .

Note that the mass spectra from the two encounters are similar, in spite of the presence or absence of a jet, and, as shown in Fig. 3, there is no experimental evidence for a significant flattening of the mass spectrum down to the lowest mass measured, contrary to the predictions of various models^{5,6} that the differential spectrum should peak, as indicated in Fig. 3. Indeed, the first particles encountered at the 'fringes' of the coma (637,000 km inbound for Vega 1; 255,000 km inbound for Vega 2) had the lowest masses measured, instead of the higher masses predicted by the 'fountain' model first introduced by Eddington⁷ and later widely developed to predict the mass distribution of cometary dust^{5,6}.

These observations, together with our observed mass spectrum, suggest that the solar radiation pressure acting on the lightest coma dust particles is smaller than suggested in the literature⁶. Alternatively, if some dust particles are comprised of much smaller particles held together by a substance which sublimates, these very small secondary particles could appear at greater distances from the nucleus.

The instrumentation was designed, built and tested in the Laboratory for Astrophysics and Space Research of the Enrico Fermi Institute, University of Chicago. It was included in the Vega missions at the invitation of R.Z.S. We thank the many individuals who helped make this US-USSR space collaboration possible, notably, R. Reinhard, A. Richter, E. Grün, L. Eagleburger and G. Briggs. Support for this experiment was provided by the USSR Space Research Institute, NASA contract NAS-W-3959, and the Arthur H. Compton Fund.

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Composition of comet Halley dust particles from Vega observations

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The dust impact mass analyser (PUMA) carried by the spacecraft Vega 1 and Vega 2 has provided the first direct measurements of the physical and chemical properties of cometary dust. Particles of mass $< 10^{-14}$ g are much more abundant than was predicted by models¹. Most of the particles are rich in light elements such as H, C, N and O, lending support to models that describe cometary material as consisting of radiation-processed ices. Three examples of mass spectra for typical particle compositions are shown.

The heart of the PUMA instrument is a time-of-flight mass spectrometer as described, for example, in ref. 2. When a dust particle strikes the target in front of the spectrometer, ions are formed, and those with positive charge are mass-analysed. On-board electronics and microprocessor-control allow the instrument to adapt to the cometary environment, and provide data compression. The instrument design was as close as possible to that of the corresponding instrument PIA, carried by the Giotto spacecraft. The PUMA and PIA instruments are described in greater detail elsewhere^{3,4}.

For the design of the instrument several assumptions had to be made; concerning, for example, the number and size distribution of particles that would hit the target, the chemical and physical nature of the cometary dust particles, and the nature of the process which leads to the formation of positive ions upon particle impact. Based on the cometary dust emission model given in ref. 1, a target area of 5 cm^2 was chosen, assuming a fly-by distance of 10,000 km. This was thought to be sufficiently large to record enough impacts but also not too large, taking into account changes in the comet's activity and the ability to handle up to 100 impacts per second. Our model for cometary dust particles was the 'Brownlee particles'⁵ with a fluffy structure

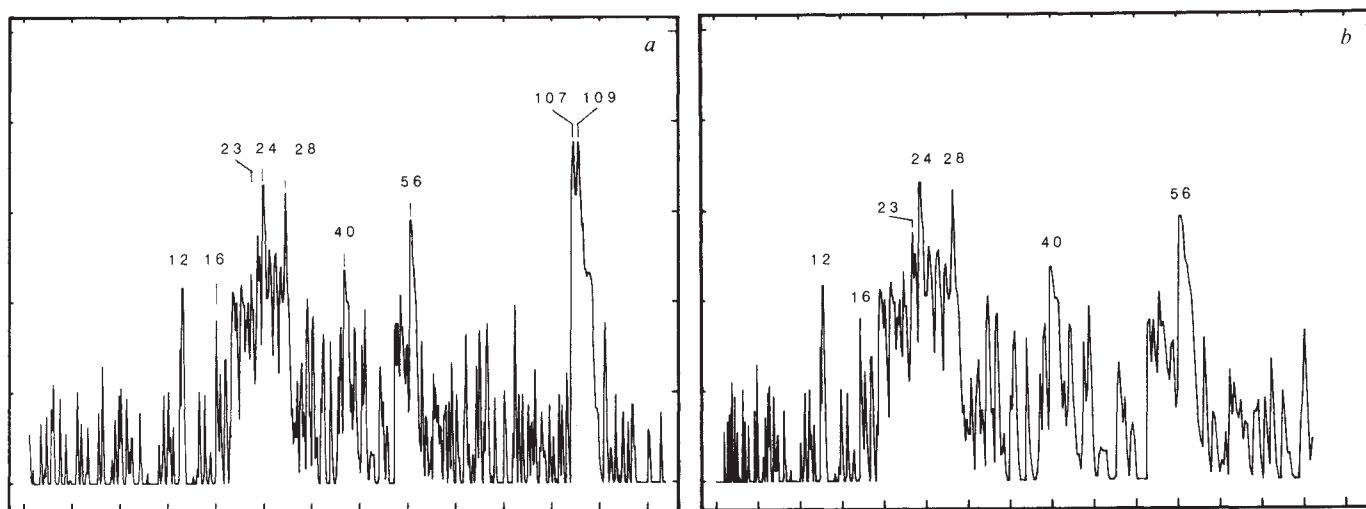


Fig. 1 Mass spectrum of a cometary particle measured by PUMA-1, aboard Vega 1 (internal reference no. 51341). *a*, Original time-of-flight spectrum; *b*, same data plotted as mass spectrum, up to mass 70 AMU. Intensities are plotted logarithmically, but not calibrated. This mass spectrum may be regarded as being closely related to a particle of type C1 carbonaceous chondrite composition. See text for further explanation.

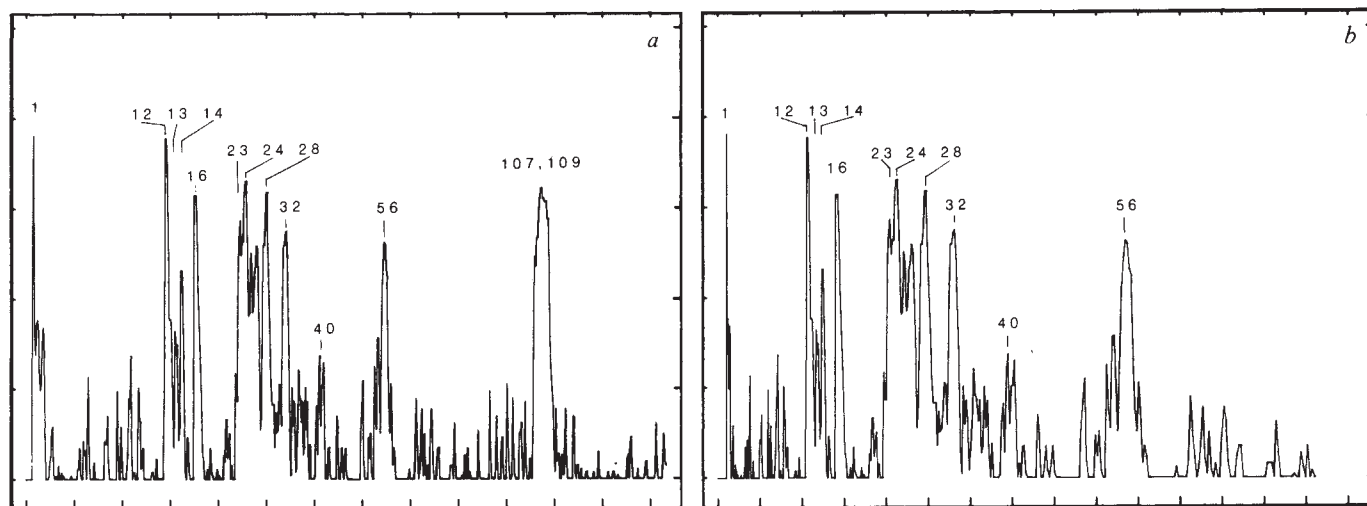


Fig. 2 Mass spectrum of a cometary particle measured by PUMA-1, aboard Vega 1 (internal reference no. 54955). See Fig. 1 legend. This mass spectrum may be regarded as representing the majority of spectra measured. See text for further explanation.

and a chemical composition corresponding to type C1 carbonaceous chondrite.

The kinematics of the particle impact and subsequent ion formation can be simulated numerically, in one or more dimensions. These analyses provide values for the pressure and temperature during different phases of an impact. Assuming (at least local) thermal equilibrium, the degree of ionization for various elements can be calculated using a Saha equation⁶; however, an alternate model assumes ion formation by desorption processes⁷. These unresolved controversies were accommodated by the use of different targets in the various flight models: a corrugated silver target for PUMA-1 (on Vega 1), a silver foil target for PUMA-2 (on Vega 2) and a silver-doped platinum foil target for PIA (on Giotto).

After health checks of the Vega instruments during the cruise phase, they were first switched on in their fully operational configuration three days before encounter. Both units functioned as expected throughout and after the encounter. Whereas PUMA-1 returned data for >1,000 dust particles, PUMA-2

suffered from bus voltage problems on Vega 2, probably due to a heavy operational load of the pointing platform. The instrument performance was fully recovered shortly before closest approach; the value of its multiplier high voltage, however, remained at its starting value. Thus PUMA-2 provided a few hundred mass spectra, predominantly of larger particles. From the number of Ag ions detected (from the target), the masses of the incident particles can be estimated to be mostly of the order of 10^{-16} g, which is lighter than predicted from the dust models developed for these missions¹.

As described in refs 2 and 3, ~3% of the data were transmitted in the so-called 'mode 0', the mode directly accessible for mass number allocation and assessment of instrument performance. However, in this mode the instrument works like a transient recorder at 15 MHz, which means that mass peaks may not have been sampled at their maximum.

Looking through the data of both PUMA-1 and PUMA-2, it appears that the mass spectra can be classified into three distinct types, of which examples are given in Figs 1-3. These are

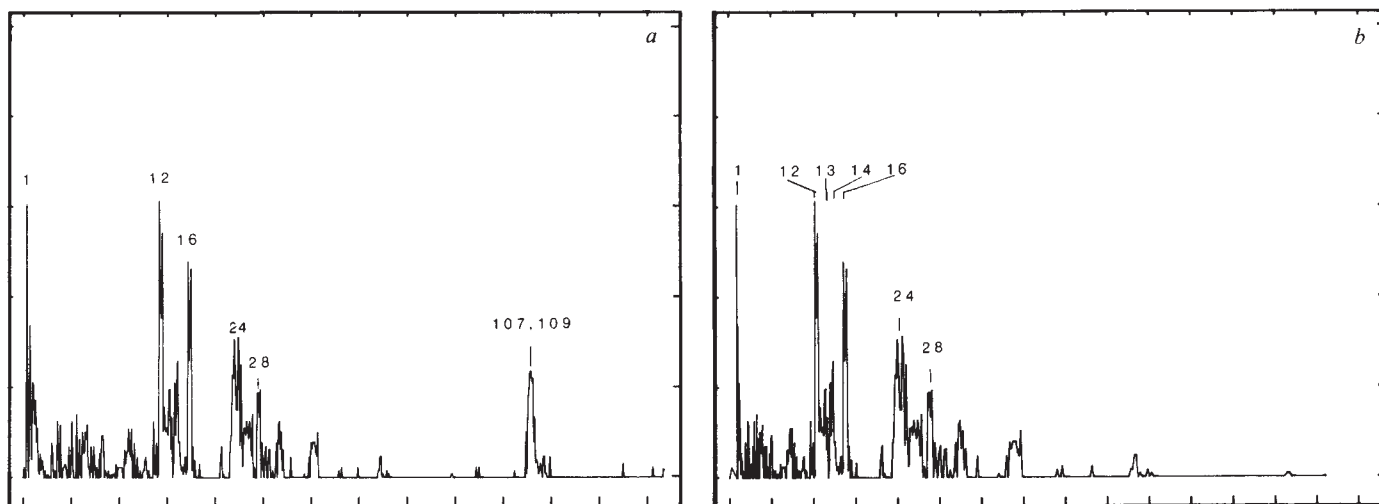


Fig. 3 Mass spectrum of a cometary particle measured by PUMA-1, aboard Vega 1 (internal reference no. 51445). See Fig. 1 legend. This mass spectrum may be regarded as typical for particulates composed predominantly of light elements. See text for further explanation.

unprocessed spectra, from which the effects of instrument characteristics have not been removed. The validity of the small peaks will have to be proved by summing several spectra. Each spectrum is plotted both as a mass spectrum (upper part of each figure), and as a time-of-flight spectrum (lower part), as originally measured. The logarithmic intensity scale shows only the expected sensitivity. The figures are used to illustrate the important features of the data; they are by no means suited to a more detailed interpretation.

The mass spectrum in Fig. 1 is characterized by its dominant mass lines, which are—apart from the contribution of the target material Ag at 107 and 109 AMU—the peaks at 12, 16, 23, 24, 28, 40 and 56 AMU, indicating the presence of C, O, Na, Mg, Si, Ca and Fe. (No peaks were observed at half the atomic mass of Ag; we therefore assume that all ions are singly charged.) These particles may be closest in composition to the C1 carbonaceous chondrites, which was expected. The mass spectrum in Fig. 2 differs from that in Fig. 1 mainly in having peaks at 1, 12, 13, 14 and 32 AMU, indicating a material richer in carbon, nitrogen, and sulphur.

The mass spectrum in Fig. 3 shows dominant peaks at 1, 12 and 16 AMU, with almost no contributions at 24, 28 and higher values. These may be particles with only a small or perhaps no mineral core. Examining all the mass spectra, including those taken in modes with higher data compression, it is striking that ~80% of all spectra seem to be of the type shown in Figs 2 and 3; the remainder are similar to that in Fig. 1. The apparent high content of carbon and nitrogen makes it difficult to accept type C1 carbonaceous chondrites as the sole chemical model for cometary dust particles.

The mass spectra of the type shown in Fig. 3 may indicate that some of the cometary material released may be ice-processed by ionizing radiation as proposed in ref. 8, and thereby converted to a non-volatile compound. The composition of other particles may support the formation model proposed in ref. 9, in which comets are aggregates of interstellar dust particles, consisting of a silicate core embedded into a non-volatile organic mantle, produced from ices by ultraviolet radiation before solar nebular condensation. Gross isotopic anomalies have not been detected as yet.

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First *in situ* plasma and neutral gas measurements at comet Halley

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We present the first *in situ* observations and a description of the large-scale behaviour of comet Halley's plasma environment. The PLASMAG-1 experiment, carried aboard the spacecraft Vega 1 and Vega 2, had the following aims: (1) to study the change of plasma parameters and distributions as a function of distance from the nucleus; (2) to investigate the existence and structure of the cometary bow shock; (3) to determine the change in chemical composition of the heavily mass-loaded plasma as the spacecraft approached the comet; and (4) to measure the neutral gas distribution along the spacecraft trajectory. We observe a discontinuity (the 'cometopause') between the solar-wind-controlled cometary sheath and heavy-ion mantle and the magnetized cometary plasma region. From the measured neutral gas density distribution we estimate a total gas production rate of 1.3×10^{30} molecules s^{-1} .

Each Vega spacecraft carried a plasma instrument package (PLASMAG-1) comprising six different sensors^{1,2}. Two hemispherical electrostatic analysers observed the energy spectra of ions arriving from the spacecraft-comet relative velocity direction and from the direction of the Sun. These sensors will be

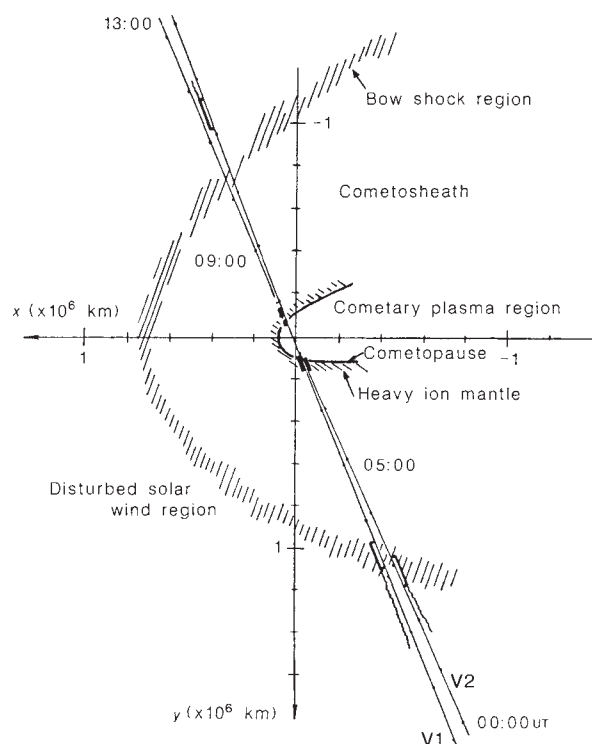


Fig. 1 The plasma environment of comet Halley, as observed by Vega 1 and Vega 2, projected on the spacecraft orbital plane. The x -axis points from the comet nucleus to the Sun. Features of the PLASMAG-1 data are marked with symbols along the spacecraft trajectories (V1, V2), which are marked at 1-h intervals of Universal Time. Wavy lines, region of disturbances in the solar-wind plasma distribution; open rectangles, heavily structured bow shock region; solid rectangles, heavy-ion mantle (see Figs 2, 3).

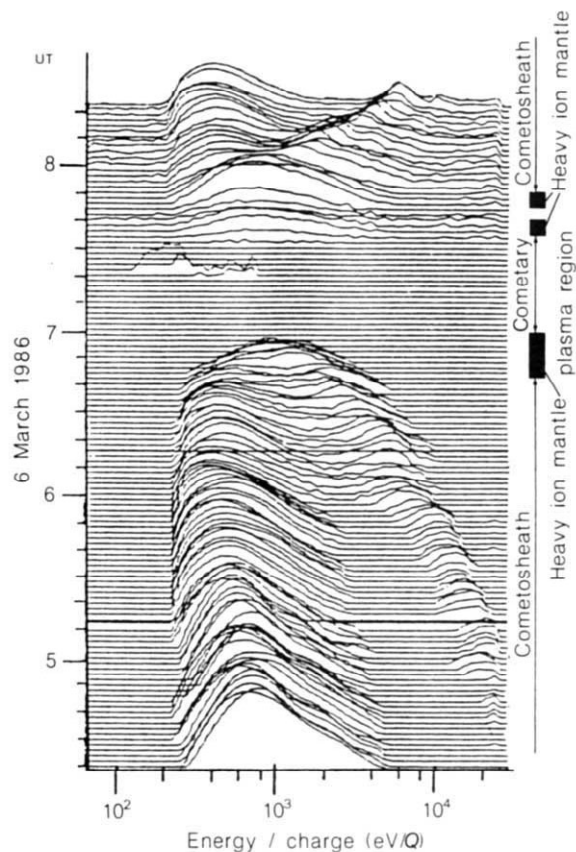


Fig. 2 High-time-resolution ion energy spectra (2-min averages) measured by the Vega 1 solar direction analyser (SDA) during encounter. Annotations refer to the regions shown in Fig. 1.

referred to as the cometary ram analyser (CRA) and solar direction analyser (SDA), respectively. Because of the three-axis stabilization of the spacecraft, electrostatic lenses were installed at the entrance slits of both ion analysers in order to widen the acceptance angle without decreasing the energy resolution. The CRA had an acceptance angle of $14^\circ \times 32^\circ$ and detected ions in the energy/charge range $15\text{--}3,500 \text{ eV}/q$ (where q is the charge state), in 120 logarithmically spaced intervals which provided a complete coverage of this range without any gaps. The SDA had an acceptance angle of $38^\circ \times 30^\circ$ and measured ions in the range $50\text{--}25,000 \text{ eV}/q$ in 60 logarithmically spaced energy intervals. All acceptance angle data presented refer to the 10% level; for the same level, the energy resolutions of both the CRA and SDA were $\Delta E/E = 0.055$.

A cylindrical electrostatic electron analyser with an acceptance angle of $7^\circ \times 7^\circ$ was oriented perpendicular to the ecliptic plane. It had 30 logarithmically spaced intervals with $\Delta E/E = 0.075$ in the energy range $3\text{--}10,000 \text{ eV}$.

The energy spectra of the ions and electrons were continuously measured at a rate of 1 per s for $\sim 4 \text{ h}$, beginning 3 h before the time of closest approach to the nucleus. During the 2 days before and 1 day after closest approach, spectra were continuously measured at a rate of 0.35 per min.

PLASMAG-1 also included two Faraday cups. The solar direction Faraday cup, with an acceptance angle of $84^\circ \times 84^\circ$, measured the solar-wind ion flux. The ram Faraday cup (RFC), with an acceptance angle of $25^\circ \times 25^\circ$, has four periodically changed modes of operation. Two of these modes provided information on the neutral particle flux from the comet, by detecting the secondary electrons produced by neutrals striking

the metallic emitter; the other two modes measured the total charged particle flux.

The final sensor included in the PLASMAG-1 package was an impact plasma detector, for measuring neutral particle flux. This detector was similar to the one developed by R. Grard at ESTEC for the Giotto mission, and its results will not be discussed here.

Figure 1 shows a schematic representation of the various plasma regions observed during the Vega 1 and Vega 2 encounters. On the inbound legs both SDAs measured a relatively fast solar wind (velocity $u \approx 510$ and 620 km s^{-1} , respectively). The first sign of the comet was detected by the CRA, which observed ions of cometary origin as far as $5 \times 10^6 \text{ km}$ from the nucleus.

As the spacecraft approached the bow shock region, disturbances started to appear in the solar-wind plasma distributions (wavy lines in Fig. 1). At a distance of $\sim 1.1\text{--}1.2 \times 10^6 \text{ km}$ from the nucleus, both Vega spacecraft encountered a broad ($\sim 10^5 \text{ km}$), heavily structured bow shock region and then entered a region of decelerated plasma, the 'cometosheath', where the proton distribution broadened significantly, so that the peak of α -particles became indistinguishable in the energy spectrum. (The width of the transition region between the solar wind and the cometosheath is small compared with its distance from the nucleus: for this reason we use the term 'bow shock', rather than 'bow wave', which was applied to the transition region at comet Giacobini-Zinner³.) The direction of the plasma stream was no longer anti-sunward, as the CRA and SDA detected proton fluxes of approximately the same energy. Vega 2 observed some oscillations in the direction of the plasma flow, protons sometimes disappearing from the SDA spectra and appearing in the CRA spectra, and vice versa.

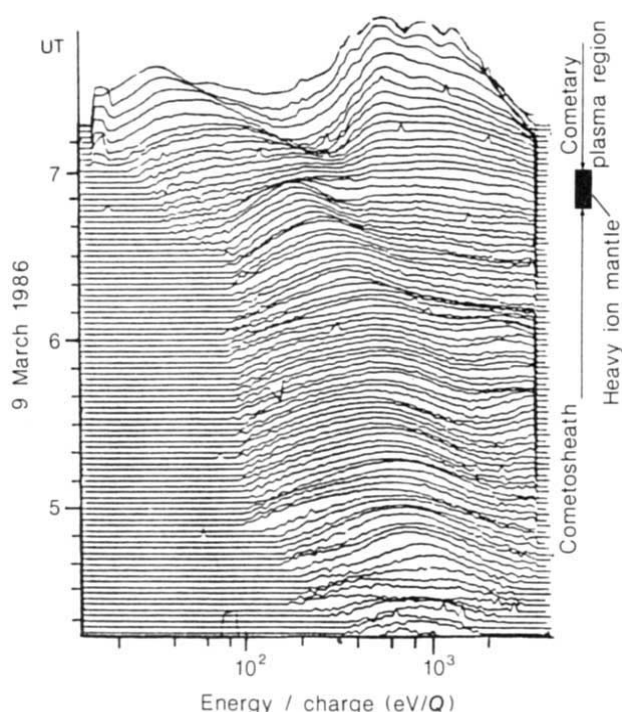


Fig. 3 High-time-resolution ion energy spectra (2-min averages) measured by the Vega 2 cometary ram analyser (CRA) during encounter. Annotations refer to the regions shown in Fig. 1.

On the outbound leg Vega 1 observed a broad, eroded bow shock region at a distance of $\sim 1.1 \times 10^6$ km from the nucleus before re-entering the solar wind ($u \approx 380$ km s $^{-1}$).

Figure 2 presents 2-min averages of the high-resolution SDA spectra measured by Vega 1 during the 4 h of high-speed data transmission near closest approach. At a distance of $\sim 8 \times 10^5$ km from the nucleus (04:20 UT), a single broad peak dominates the spectra, corresponding to a shocked solar-wind proton flow with a velocity of ~ 350 – 400 km s $^{-1}$. Closer to the nucleus a second peak appears in the SDA spectra which corresponds to a much higher energy than that of the solar-wind protons. This second peak must be produced by cometary ions (probably of the H₂O group), because solar-wind ions never have such a high energy.

At a distance of $\sim 3 \times 10^5$ km from the nucleus (06:15 UT), the solar-wind proton population becomes comparable to the cometary implanted ions. From Fig. 2 and the Vega 2 data, one may conclude that at $\sim 1.5 \times 10^5$ km from the nucleus (06:45 UT), the original solar-wind population effectively disappears from the solar direction; instead, the SDA observes mainly a broad distribution of slow cometary ions. This region can be called the 'heavy ion mantle', where the plasma is moving slowly around the cometary obstacle. Shortly afterwards, at $\sim 1 \times 10^5$ km (07:00 UT), the SDA stops detecting particles. On the outbound pass, the cometary ions reappear in the SDA at $\sim 7 \times 10^4$ km from the nucleus (07:35 UT), after which the shocked solar-wind protons can again be observed.

Figure 3 shows 2-min averages of the high-resolution spectra obtained by the Vega 2 CRA, starting at $\sim 8 \times 10^5$ km from the nucleus (04:20 UT); that is, well downstream of the bow shock region. Between 8×10^5 and $\sim 1.5 \times 10^5$ km (06:45 UT), the CRA observes a broad distribution of decelerated protons. These particles are probably diverted solar-wind protons with largely randomized velocities which were observed simultaneously by the SDA. Signatures of heavy cometary ions can be seen in the upper part of the measured energy range, and simultaneous SDA data (not shown here) indicate that at $\sim 1.5 \times 10^5$ km from

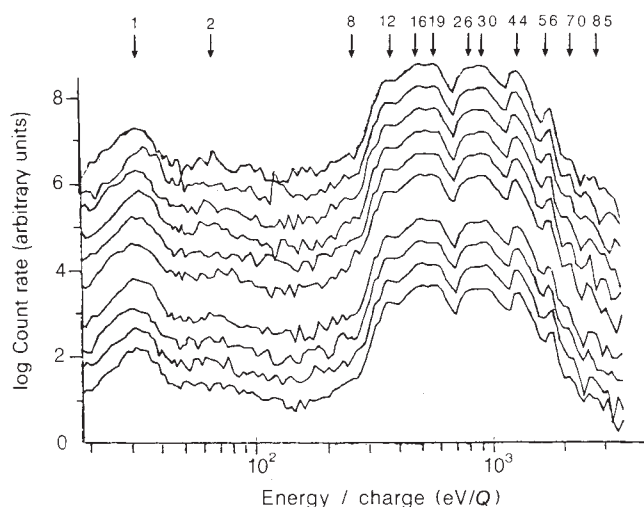


Fig. 4 Ion energy spectra (1-s averages) measured by the Vega 2 CRA at a distance of 1.5×10^4 km from the nucleus. Some of the mass/charge (M/q) peaks are identified in the text.

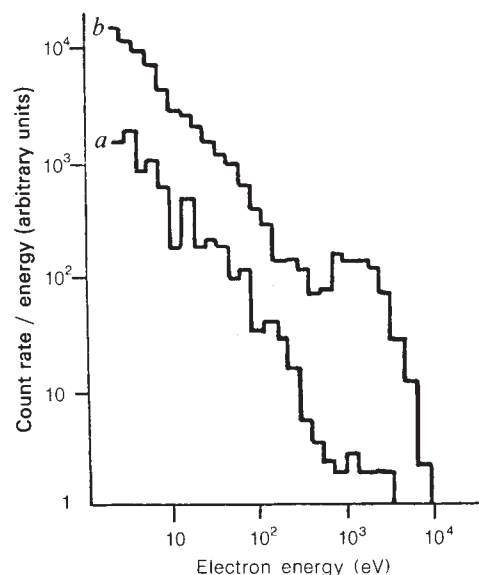


Fig. 5 Electron energy spectra measured in the solar wind (a, 07:03 UT, 11 March) and at a distance of 1.5×10^4 km from the nucleus (b, 07:17:29 UT, 9 March).

the nucleus, the solar-wind proton population is replaced by a slowly moving layer of heavy cometary ions (the heavy ion mantle observed by Vega 1).

At $\sim 1 \times 10^5$ km (06:55 UT), the spacecraft entered the cold, almost stagnant or only very slowly moving cometary ion region which is characterized by increasing ion fluxes in the 300–3,000 eV/ q range. This region is inhomogeneous, comprising extended stratified zones with layers of regularly varying density (corresponding to a characteristic length along the orbit of ~ 800 km). At $\sim 1.5 \times 10^4$ km the CRA detected only cold cometary ions and it is possible to carry out a mass analysis of these heavy ions. Unfortunately, not long afterwards the plasma instrument became temporarily disabled by exposure to the harsh cometary environment.

Figure 4 shows expanded versions of several successive 1-s spectra measured by the CRA in the cometary plasma region. The first peak is due to H⁺ ions, ≈ 30 eV, indicating a velocity nearly equal to the spacecraft-comet relative velocity, $v_R =$

76.78 km s^{-1} . This indicates that the cometary plasma is 'cold'; that is, both the bulk and thermal velocities of these ions are much smaller than v_R . The peaks of the other ions then correspond to $E/q = 30.55M/q$, where M is the mass in AMU. Some M/q values are indicated in Fig. 4. Assuming that these ions are predominantly singly charged, the CRA energy spectra shown in Fig. 4 can be used for mass spectrometry.

From Fig. 4, H^+ , C^+ , CO_2^+ and Fe^+ ions can be identified with confidence. The peak at $14 \leq M/q \leq 20$ most probably originates from H_2O parent molecules with some possible contribution of CH_4 and NH_3 . There are two secondary peaks at $M/q = 16-17$ and $M/q = 19$, possibly corresponding to O^+ , OH^+ and H_3O^+ ions, respectively. The identity of the $24 \leq M/q \leq 34$ peak is less certain, and it probably originates from several parent molecules, such as CO , CO_2 , and N- or S-bearing molecules.

Figure 4 is based on channeltron count rates, which reach the level of $\sim 8 \times 10^5 \text{ counts s}^{-1}$ at the major peaks. At such rates the channeltrons which were used operate in a nonlinear regime: significant flux increases result in only small changes in count rate. This effect will be taken into account in later publications.

Figure 5 shows two typical electron spectra: one was measured deep in the cometary plasma region and the other was obtained 2 days later in interplanetary space. A major difference between the two spectra is the appearance of a very energetic (few keV) electron population. These electrons might be an additional effective source of ionization in the coma.

Figure 6 shows a preliminary neutral gas density profile determined from the RFC data. When estimating the neutral density values, a secondary electron yield of 0.3 was assumed for incident neutral particles with a velocity of $\sim 80 \text{ km s}^{-1}$. The dashed line in Fig. 6 represents a simple fit to the data assuming an $r^{-2} \exp(-r/\lambda)$ neutral density dependence on the distance r from the nucleus. The ionization scale length λ was estimated to be $2 \times 10^6 \text{ km}$, and a value of $1.3 \times 10^{30} \text{ molecules s}^{-1}$ was obtained for the total gas production rate, assuming a neutral gas velocity of 1 km s^{-1} .

The data shown in Fig. 6 were obtained during the inbound pass of the Vega 1 fly-by. On the outbound leg a more compli-

cated neutral gas density distribution was observed, indicating significant spatial and temporal deviations from a simple r^{-2} dependence. We estimate the uncertainty of our preliminary analysis to be a factor of 2-3.

As discussed above, both Vega spacecraft crossed a wide and structured bow shock region at $\sim 1.1 \times 10^6 \text{ km}$ from the nucleus. This bow shock is not the result of a dynamic compression of the solar wind at a 'hard' obstacle, but is produced by the continuous mass loading of the solar wind by newly created cometary ions⁴⁻⁸. It was found that the mass-loaded, shocked plasma flow is dynamically controlled by the solar wind between the bow shock and the 'cometopause', observed at a distance of $1 \times 10^5 \text{ km}$ from the nucleus, which separates the solar-wind-controlled cometosheath and heavy-ion mantle from the magnetized⁹ cometary plasma region. This magnetized cometary plasma region behaves as an obstacle to the mass-loaded solar wind flow, and its volume, which is controlled by the comet, is much larger than was theoretically predicted^{4,5}. According to previous theoretical calculations only the plasma region inside the contact surface is dynamically detached from the solar wind. The relative contributions of the magnetic field and the various plasma components to the pressure balance across the cometopause will be the subject of a future study.

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First observations of energetic particles near comet Halley

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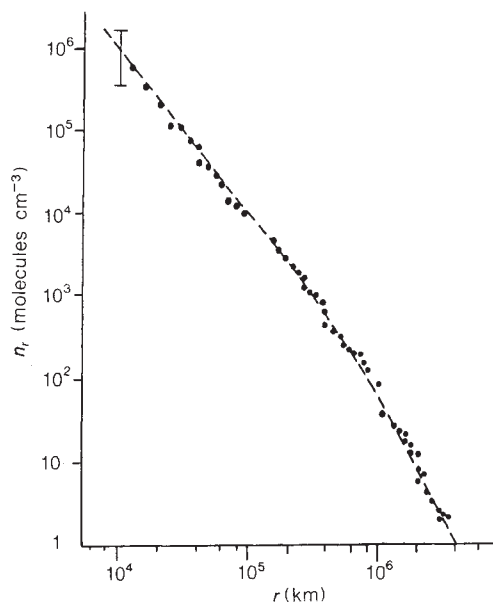


Fig. 6 Neutral gas density profile determined from the ram Faraday cup (RFC) data. The data are fitted to a curve of the form $n_r = n_0(r_0/r)^2 \exp(-r/\lambda)$, where n_r is the neutral gas density at distance r from the nucleus, $r_0 = 10^5 \text{ km}$, and the ionization scale length $\lambda = 2 \times 10^6 \text{ km}$. The gas production rate Q was estimated as $Q = 4\pi r_0^2 n_0 v_g$, where the neutral gas velocity v_g was assumed to be 1 km s^{-1} .

The TUNDE-M energetic particle instrument aboard the Vega 1 spacecraft detected intense fluxes of energetic ($\geq 40 \text{ keV}$) ions in the vicinity of comet Halley, starting at a distance of 10^7 km from closest approach. Three regions of differing ion characteristics have been identified. An outer region, several million kilometres

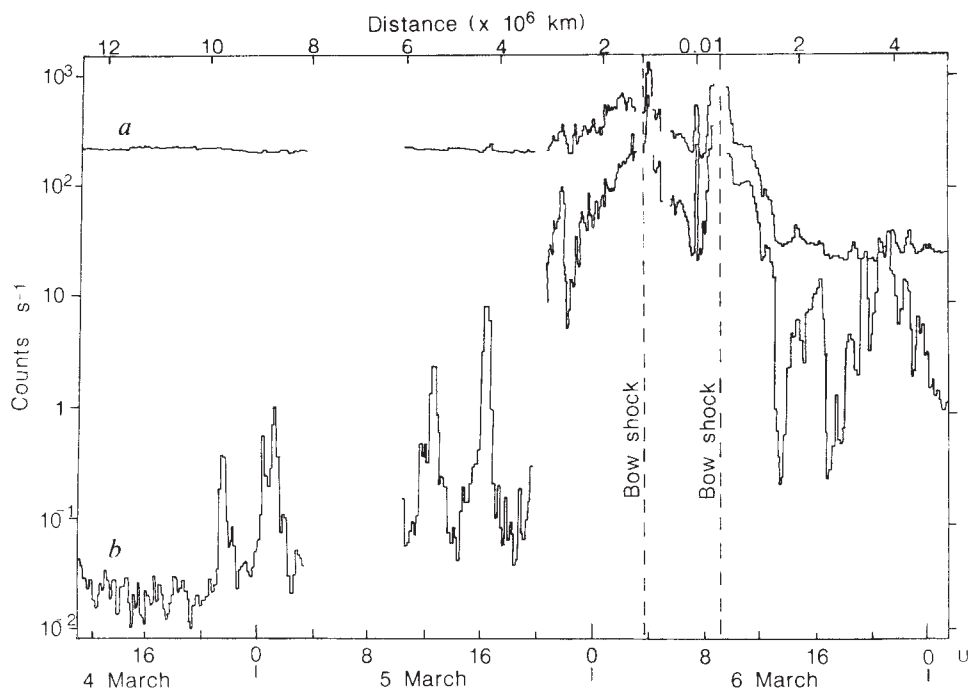


Fig. 1 Ion flux recorded on 4-6 March 1986 by the two lowest-energy channels of the Vega 1 TUNDE-M. *a*, 40-50 keV; *b*, 50-60 keV. The upper horizontal scale is the distance of the spacecraft from the comet nucleus. The high level of flux seen in the lowest-energy channel (curve *a*) until 20:00 on 5 March is probably due to temporarily increased instrumental background. The outbound shock cannot be located unequivocally: the position indicated is a possible location deduced from our measurements, combined with magnetic observations¹⁵.

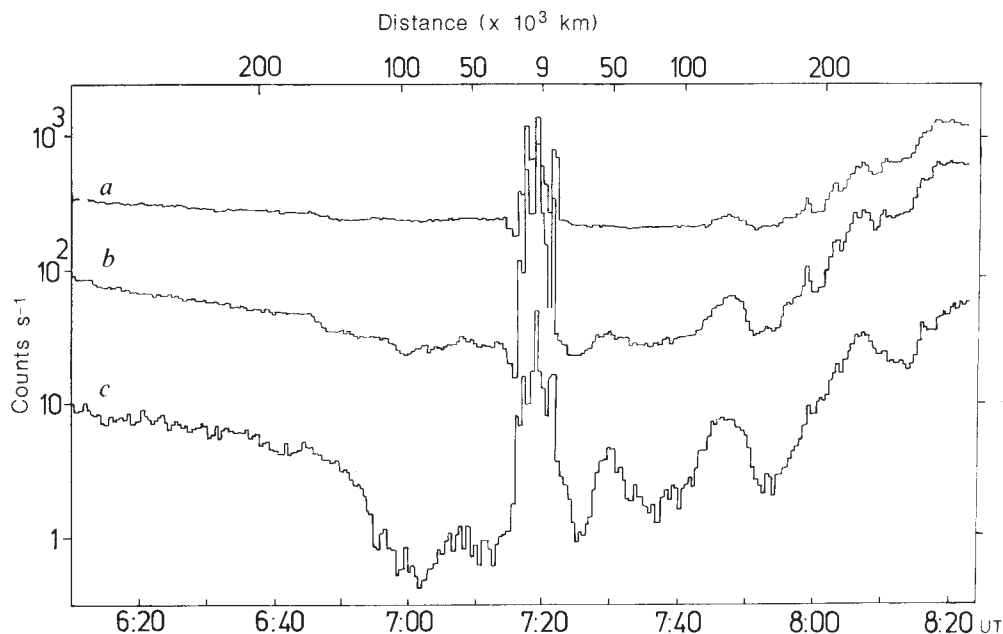


Fig. 2 An expanded version of the region of Fig. 1 near the time of closest approach to the nucleus (07:20 UT on 6 March).

in extent, contains pick-up ions in the solar wind. A second region, inside the bow shock (several hundred thousand kilometres in extent), contains the most intense fluxes, whereas the innermost region (several tens of thousands of kilometres) is characterized by lower intensities and sharp spikes near closest approach ($\sim 8,900$ km from the nucleus).

Cometary ions are created from cometary neutrals by photoionization and charge exchange with solar-wind particles. The newly created cometary ions are approximately at rest; they are then accelerated by the solar-wind electric field, E , resulting at first in cycloidal motion in the $E \times B$ direction, where B is the interplanetary magnetic field^{1,2}. The cometary ion distribution function forms a ring in velocity space, drifting parallel to B (refs 2, 3). This type of distribution is highly unstable and generates magnetic fluctuations which scatter the ions in pitch angle, and thereby make the distribution nearly isotropic^{1,4}. The traversal of the bow shock by ions created upstream is expected to lead to further acceleration and energization of these ions^{2,4,5},

either by gradient drift and/or Fermi acceleration or by adiabatic compression. Further acceleration of cometary ions downstream of the bow shock could be caused by first- and second-order Fermi processes, adiabatic compression (most important in the magnetic barrier region close to the nucleus), and by magnetic reconnection up- and downstream of the nucleus. The result of these processes is that H_2O^+ ions, for example, can be accelerated up to energies of several hundred keV or even up to MeV energies^{5,6}.

The Vega mission and spacecraft trajectories are described elsewhere⁷. The trajectories form an angle of $\sim 110^\circ$ to the Sun-comet axis, and the TUNDE-M telescope points normal to this axis in the ecliptic plane, in a direction roughly opposite to the spacecraft motion^{8,9}. The TUNDE-M telescope measures ions, within a cone of half-angle 25° , in 10-keV bins for energies ranging from 40 to 490 keV, and in 20-keV bins for 490 to 630 keV. Other channels for higher-energy electrons, protons and ions are not discussed here. TUNDE-M is not able to

distinguish the mass of an incident ion at a given energy; however, only heavy ions picked up by the solar wind and further accelerated by the processes outlined above are expected to have sufficient energy to be detected.

Figure 1 shows two typical TUNDE-M records; expanded plots of the fluxes observed near the time of closest approach are shown in Fig. 2. The energies indicated in Figs 1–3 are those deposited as ionization energy in the silicon layer of the topmost detector of the TUNDE-M telescope, by incident ions that were totally absorbed in that layer. For protons, these energies are very close to the incident energies, but for a heavy ion the energy deposited in the silicon layer may be considerably less than the incident energy (for details, see ref. 10). The contamination of the measured ionic fluxes by electrons was negligible during the period of observation discussed here, partly because of a deflecting magnet applied to the top detector, and partly because of the anti-coincidence condition requiring total absorption of the particles in the top detector^{8,9}.

Three regions can be distinguished in Figs 1 and 2: (1) An outer region well outside of the in- and outbound shock crossings, which took place at distances of $\sim 10^6$ km (refs 11, 15) and $\sim 5 \times 10^5$ km (see Fig. 1 legend), respectively, from the nucleus. Energetic ions are detected as far as 10^7 km from the nucleus; the scale length of this region is $\sim 10^6$ km. (2) A region containing the most intense fluxes, including the shock¹⁵ and most of the cometsheath¹¹. The extent of this region is several hundred thousand kilometres. (3) An inner region characterized by a reduced flux level and by superimposed flux enhancements. The scale length of this region is several tens of thousands of kilometres. Near closest approach, several distinct intensity spikes are observed over a region of several thousand kilometres. Similar regions have been identified from energetic particle measurements near comet Giacobini-Zinner^{12,13}.

The outer region is characterized by an overall increase of the 50–60-keV flux with decreasing distance from the bow shock; this increase is steepest within $\sim 3 \times 10^6$ km. Superimposed on this general trend are a number of discrete flux enhancements of 1 to 2 orders of magnitude, exhibiting a quasi-periodicity of ~ 4 h. The presence of these enhancements is related to the prevailing solar-wind and magnetic field conditions. From the energy spectra a 'temperature' of ~ 5 keV can be estimated.

The ion fluxes (Fig. 1) begin to increase more rapidly as the shock is approached. The flux at higher energy increases faster; thus, the spectrum hardens. This is most probably due to acceleration at or near the bow shock or to adiabatic compression in the bow-wave region. From the energy spectrum (Fig. 3) we estimate an effective temperature of 20–40 keV near the shock. The maxima of the ion flux enhancements are found near the in- and outbound bow shock; the flux levels behind the shock in the cometsheath region (except for the depletion zone discussed below) remain approximately the same with only a moderate decrease. As the solar wind velocity decreases considerably in this region¹¹, this observation indicates further acceleration of cometary ions after pick-up, by turbulences in this region (first- and second-order Fermi processes^{5,6}). Other processes, such as isotropization of ion velocities due to enhanced magnetic turbulence, may also contribute to the observed effect.

In addition, more ions may gain access to TUNDE-M here than in the outer region, because of the possibly greater isotropy of the ion distributions in the inner region, which is probably due to the enhanced level of turbulence observed by the wave experiments on Vega-1¹⁴.

In the innermost region, which extends from $\sim 06:50$ to $\sim 08:05$ UT (Fig. 2), the energetic ion fluxes are much lower, especially at higher energies, so that the energy spectrum softens (Fig. 3). This zone of energetic ion depletion seems to correspond closely to the cometary plasma region observed by the PLASMAG¹¹ instruments in which solar-wind protons disappear, and which is also associated with the magnetic barrier regime. Two processes

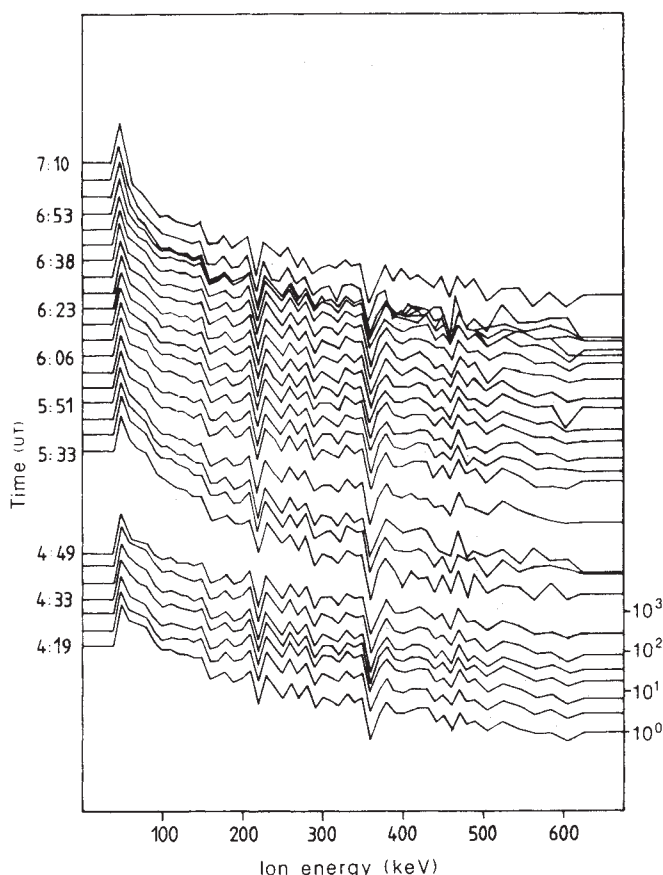


Fig. 3 Time series of ion flux versus energy profiles measured by the Vega 1 TUNDE-M during the 3 h preceding closest approach. Points represent 5-min averages of count rate (per s), multiplied (for ease of display) by $(t/5) \times 10^{0.4}$, where t is time (min) measured from 04:19 UT on 6 March 1986. The sharp decreases in count rate at 210 and 350 keV are caused by differences in the energy-channel widths, for which correction has not yet been made.

ses can probably explain these observations. First, energetic ions are depleted by charge-exchange collisions with neutrals¹. For a production rate $Q \approx 10^{30}$ molecules s^{-1} , the charge-exchange time near the edge of the depletion zone ($R \leq 10^5$ km) is estimated as 10^3 s, which is indeed comparable to the transport or convection time for an almost stagnated solar wind ($u \leq 30$ km s^{-1}). Second, energetic ions can escape from this region along magnetic field lines, because their parallel velocity for most pitch angles is much greater than the bulk velocity. In fact, 'conic' distributions should exist.

Near the closest approach of Vega 1 to the nucleus (07:20 UT in Fig. 2), a set of closely spaced, narrow peaks are evident at all energies. We note that this feature coincides with the occurrence of maximum magnetic field intensity and rapid changes in field direction¹⁵.

Finally, the flux of 160–300-keV electrons, as detected by the TUNDE-M experiment, increases very rapidly from the background counting rate at closest approach to the cometary nucleus, and stays high for ~ 4 h afterwards. No significant variation in this flux had been observed for several days preceding closest approach.

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Magnetic field observations in comet Halley's coma

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During the encounter with comet Halley, the magnetometer (MISCHA) aboard the Vega 1 spacecraft observed an increased level of magnetic field turbulence, resulting from an upstream bow wave. Both Vega spacecraft measured a peak field strength of 70–80 nT and observed draping of magnetic field lines around the cometary obstacle. An unexpected rotation of the magnetic field vector was observed, which may reflect either penetration of magnetic field lines into a diffuse layer related to the contact surface separating the solar-wind and cometary plasma, or the persistence of pre-existing interplanetary field structures.

Our present understanding of the interaction of the solar wind with the ionized gas cloud surrounding a comet derives from the pioneering work of Alfvén¹ and Biermann *et al.*² The deceleration of the solar-wind plasma in the vicinity of the comet due to mass loading bends the magnetic field lines around the inner parts of the coma and stretches the magnetic field in the anti-solar direction. The resulting configuration can be modelled by modern computer simulations³ in three dimensions; however, these simulations do not reveal where the plasma will be unstable to the production of magnetohydrodynamic plasma waves. Thus, the ICE (International Comet Explorer) spacecraft observations of strong turbulence in the vicinity of comet Giacobini-Zinner⁴ were somewhat unexpected, but are now much better understood⁵.

The magnetic field experiments MISCHA (Magnetic field in interplanetary space during comet Halley's approach) carried by Vega 1 and Vega 2 use four sensor fluxgate systems, with three sensors mounted on a boom at the end of the solar panels and a gradiometer sensor mounted one metre closer in. The instruments have a dynamic range of ± 100 nT and a sensitivity of 0.05 nT. Spectral analysis of magnetic field fluctuations in the frequency range 0–10 Hz is performed on board the spacecraft. A more detailed description can be found in ref. 6.

On 6 March 1986 (7:20:06 UT), Vega 1 passed the nucleus of comet Halley at a distance of 8,890 km with a relative velocity of 79 km s⁻¹. Vega 2 passed Halley on 9 March 1986 (07:20:00 UT) at a distance of 8,030 km and with a relative velocity of 76 km s⁻¹. Two days before the encounters the magnetometers were switched from the cruise-phase mode (TRASSA-1 mode: 1 vector per 2.5 min) to the TRASSA-2 mode (1 vector per min and 1 spectrum per 5 min). From 3 h before until 1 h after closest approach the DT-mode (direct transmission, 10 vectors per s) was switched on.

At a distance of 1.1×10^6 km the spectral channels of the Vega 1 magnetometer showed a significant increase of the turbulence in the frequency range 0.05–2 Hz (Fig. 1). During the encounter

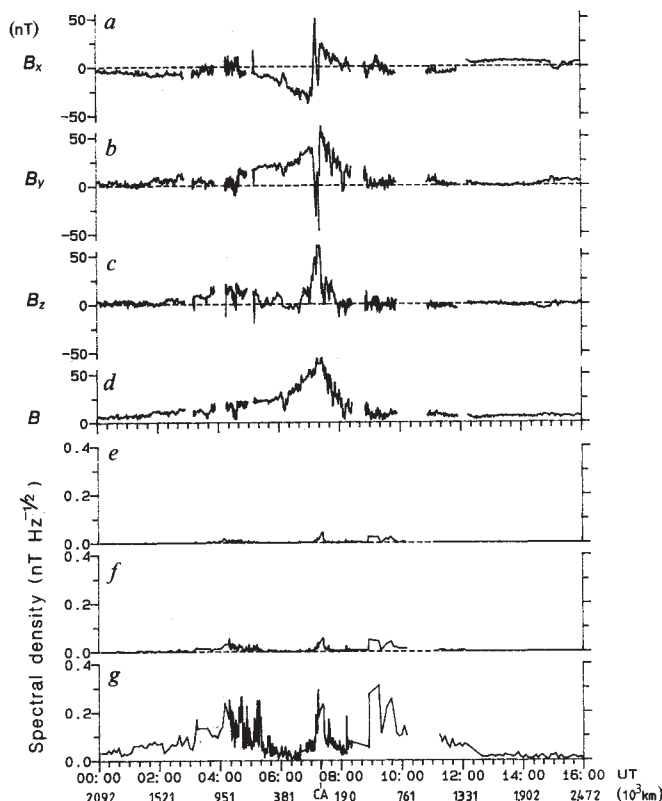


Fig. 1 Components (a-c), magnitude (d) and power spectral density (e-g) of the B_x component during the Vega 1 encounter on 6 March 1986. The spectral densities shown are for the frequency ranges 1.367–1.992 (e), 0.703–1.328 (f) and 0.039–0.664 (g) Hz. The increase of turbulence at 03:10 UT and the decay of turbulence at 12:05 can be interpreted as an inbound and outbound bow wave. The lower horizontal scale is the distance of the spacecraft from the nucleus; 'CA' denotes the closest approach to the nucleus at 07:20:06 UT (8,980 km). x , y and z are cometary solar ecliptic, (CSE) coordinates: z points towards the north pole of the ecliptic, x points from the comet towards the Sun (but parallel to the ecliptic), and y completes the right-handed coordinate system.

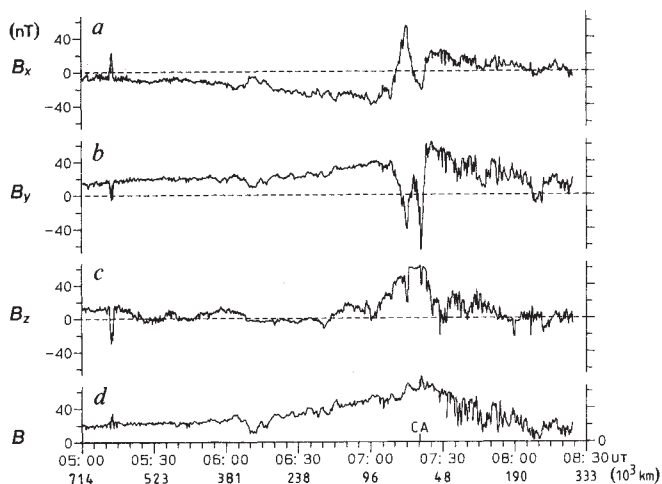


Fig. 2 High-resolution (10 vectors per s) magnetic field data from the Vega 1 encounter. CA, closest approach.

the spectral channels showed periods with varying turbulence, and afterwards at a distance of $\sim 1.3 \times 10^6$ km the turbulence level decreased to the quiet solar-wind values. The magnetic field strength increased gradually over a period of 5 h, from ~ 8 nT to a peak of 75 nT, followed by a more rapid decay over a period of ~ 2 h to solar-wind levels (Fig. 2). This asymmetry can be attributed to the trajectory of Vega 1, which approached Halley from the downstream direction at an angle of 68° to the Sun-Halley line. In the hours preceding closest approach, B_x became increasingly negative, while B_y was increasingly positive and B_z changed from northward to southward. Near closest approach both B_x and B_y oscillated, while B_z , pointing northward again, showed a pronounced maximum at ~ 60 nT.

The Vega 2 magnetometer detected an increase in total magnetic field strength to ~ 80 nT, and a change in sign of B_x near closest approach (Fig. 3). Due to a sudden event which damaged

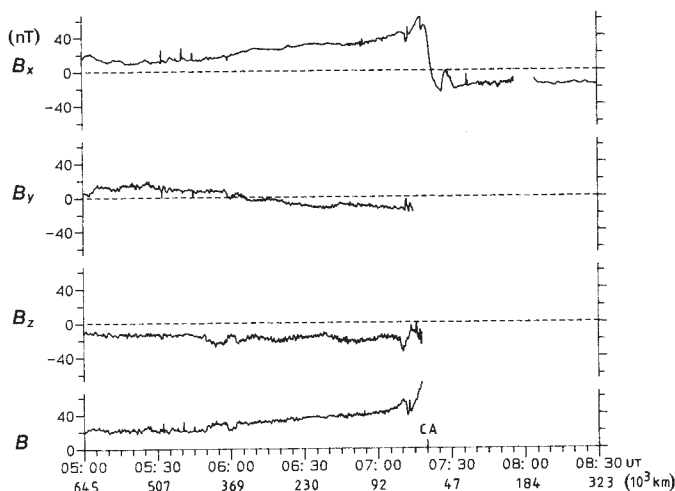


Fig. 3 High-resolution magnetic field data from the Vega 2 encounter on 9 March 1986. The lack of data for B_y , B_z and B after closest approach (CA) is due to the failure of the triaxial sensor at 07:20. For the outbound part of the Vega 2 fly-by only the data from the single-axis gradiometer sensor are available (B_x).

the triaxial sensor, only data from the fourth (single-axis) sensor are available for the outbound portion of the Vega 2 path.

Figure 4 gives details of the magnetic field behaviour near closest approach. The field vector is projected onto the x - y plane (cometary solar ecliptic coordinates; see Fig. 1 legend) and plotted along the Vega trajectory. One can clearly see the draping of magnetic field lines in the upper (to $\sim 62,000$ km) and lower (from $\sim 17,000$ km) part of the figure and a rotation of the field in between. The discontinuities at the boundaries of this interval were analysed using minimum-variance analysis, and showed the characteristics of tangential discontinuities, with vector normals $\mathbf{n}_1$ and $\mathbf{n}_2$.

The enhancement of magnetic field turbulence during the Vega 1 encounter (Fig. 1) can be interpreted as the crossing of a bow wave at a distance of $\sim 1.1 \times 10^6$ km inbound. No abrupt changes in magnetic field strength were observed; this lack of a classical bow shock is not unexpected⁷. There is some indication of a possible shock outbound at $\sim 480,000$ km, and a decrease in turbulence at $\sim 1.2 \times 10^6$ km. The Vega plasma instruments also observed discontinuities at distances of $\sim 10^6$ km (ref. 8). We use the term 'bow wave'¹² to describe this transition, which is different from the known planetary and interplanetary shocks. The level of turbulence seen by MISCHA is much less than that seen at comet Giacobini-Zinner⁴.

The structure of the magnetic field magnitude (B) during the encounter can be qualitatively explained by the piling-up of magnetic field lines due to the mass loading of the solar wind with cometary ions^{1,2}. It agrees very well with the magnetohydrodynamic simulations of Fedder^{3,9}. The reversal in the x

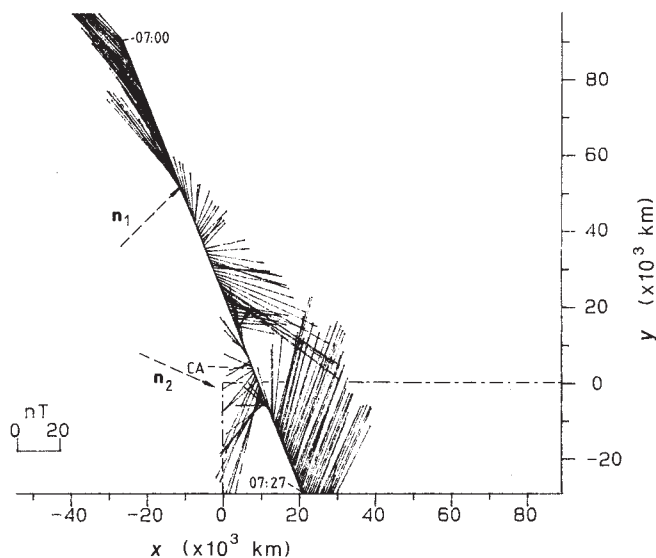


Fig. 4 Magnetic field vectors along the Vega 1 trajectory projected onto the x - y plane (CSE coordinates; see Fig. 1 legend). Draping of the magnetic field lines is observed during the intervals 07:00-07:07, and 07:23-07:27 UT. The tangential discontinuities at 07:11 and 07:24 separate the region with field-line draping from the region in which the field rotates. The normal vectors $\mathbf{n}_1$ and $\mathbf{n}_2$ have been calculated using minimum variance analysis. CA, closest approach.

component was as expected for the draped field configuration^{3,10}; however, the oscillatory structure of B_x and B_y was surprising. As there is no anomalous behaviour of the total field, one could interpret the rotation as reflecting the entry of the spacecraft into a region that was magnetized by the solar wind in some quite different direction. Because the plasma near closest approach is moving more slowly than that on either side of this point, the induced field direction may correspond to the interplanetary field at some earlier epoch.

There is, however, an alternative interpretation: the spacecraft could have entered a diffuse layer, closely related to the contact surface^{10,11} which separates the solar-wind and the cometary plasma. The classical draping of magnetic field lines cannot be observed along the Vega 1 trajectory for a period of ~ 10 min (see Fig. 4). The leading and trailing edges of this interval resemble tangential discontinuities, with normals pointing roughly in the radial directions. The trajectory intersects the boundary layer at two points, defined by the normals $\mathbf{n}_1$ and $\mathbf{n}_2$ (see Fig. 4). The observations during this interval could be explained by a penetration of magnetic field lines into this layer.

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Observations of waves and plasma in the environment of comet Halley

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The high-frequency plasma-wave analyser (APV-V) carried by the spacecraft Vega 1 and Vega 2 measured electric fields at frequencies up to 300 kHz and characteristic parameters of the ambient plasma during the encounters with comet Halley. The data collected on Vega 1 and Vega 2 are quite similar. Electric field activity at frequencies of ~ 100 Hz was already significant at a distance of $\sim 2.5 \times 10^6$ km from the nucleus. The field displayed strong fluctuations; its average amplitude and bandwidth increased drastically during the approach, and for distances less than 1.2×10^5 km a maximum was observed at 200–400 Hz. The plasma density, measured with Langmuir probes, was $\sim 10^4 \text{ cm}^{-3}$ at closest approach.

The first objective of the APV-V experiment was to detect electric fields in the bandwidth 0–300 kHz using a double sphere antenna with a baseline of 11 m; the second objective was to characterize the plasma environment with a set of two Langmuir probes. The spectrum of the signal detected by the electric antenna is analysed with a set of 16 adjacent and logarithmically spaced filters which cover the frequency range from 8 Hz to 300 kHz. The waveform of the low-frequency fluctuations (< 8 Hz) is telemetered through two channels with overlapping bandwidths of 0–0.5 and 0.1–8 Hz; the quasi-static channel (0–0.5 Hz) is sampled with 12-bit resolution. The difference in potential between the sensor and the spacecraft structure is monitored continuously; this measurement yields information about possible differential electric charging between sensor and structure. The impedance of the spherical sensors can be modified by injecting a bias current into the plasma; a level of 50 nA was selected for the encounters.

The currents collected by the Langmuir probes are processed by two independent electrometers. The polarization voltage of one probe is held at a fixed value of +5 V; that of the other consists of a sinusoidal sweep superimposed on a d.c. voltage. The amplitude of the sweep and the d.c. level can be modified by telecommand. The currents of the two probes are telemetered in the bandwidth 0–0.5 Hz; in addition, the waveform of the current fluctuations collected by one probe is transmitted in the bandwidth 0.1–4 Hz. More detailed information about the characteristics and nominal performances of the experiment can be found in refs 1–4.

The instrument on Vega 1 worked perfectly and gave valuable data up to 07:14:17 UT on 6 March 1986, when the spacecraft was at an inbound distance of 28,600 km from the nucleus. At this time the experiment abruptly stopped working, probably because of damage due to a dust particle. The instrument on Vega 2 worked throughout the fly-by, but suffered partial damage at closest approach.

As had been expected³, the APV-V was one of the first Vega instruments to detect the influence of the comet: an increase in electric field strength was detected at distances of ~ 1.2 – 2.5×10^6 km from the nucleus. It is not clear whether this increase is connected with a bow shock. The average amplitude and bandwidth of the electric field increased markedly during the approach to the comet. The upper frequency limit of the noise

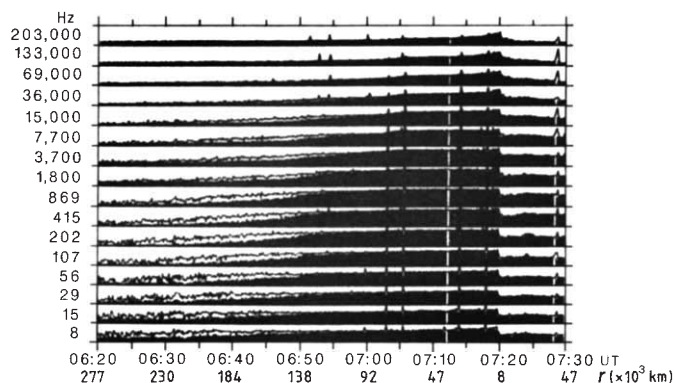


Fig. 1 Wave electric field intensity measured by the filter bank on Vega 2 during successive 8-s intervals. The solid black gives the average intensity; the thin line represents the average 2σ , where σ is the standard deviation associated with each average. The central frequency of each filter is given on the ordinate. Each vertical axis represents a dynamic range from -70 to $+10$ dB; 0 dB corresponds to 1 V r.m.s. r is the distance of Vega 2 from the nucleus. The signal reduction observed at closest approach (07:20 UT) results from a loss of sensitivity, probably due to damage caused by dust impacts. Spikes observed simultaneously in all filters are caused by data gaps.

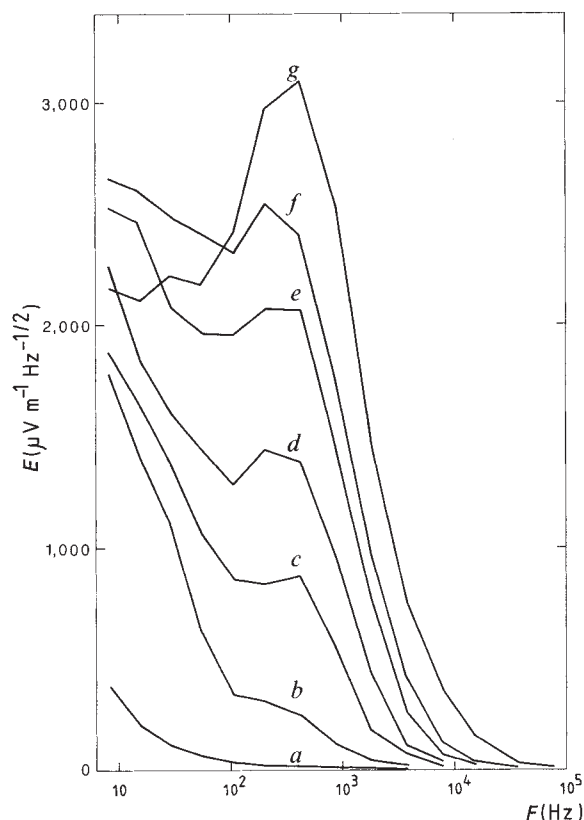


Fig. 2 Sequence of averaged (2-min) spectra measured by Vega 1 at distances from the nucleus of: a, 1.8×10^5 ; b, 1.4×10^5 ; c, 1.2×10^5 ; d, 1.1×10^5 ; e, 9×10^4 ; f, 6×10^4 ; and g, 4×10^4 km. A maximum was observed in the spectra at 200–400 Hz at distances $< 1.2 \times 10^5$ km.

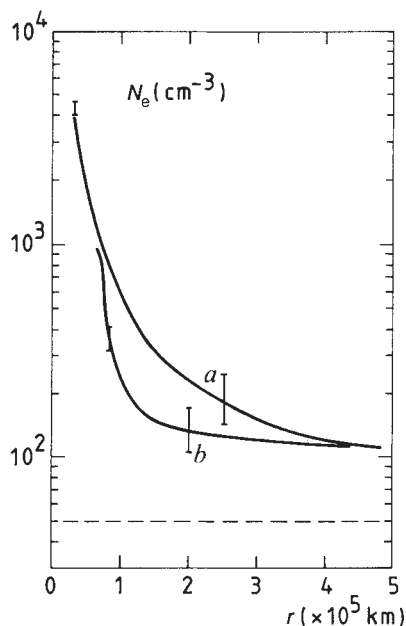


Fig. 3 Preliminary electron density profiles observed by Vega 1 (a) and Vega 2 (b). The horizontal dashed line indicates the sensitivity of the instrument.

seems to be consistent with the plasma frequency, which can be calculated from the electron density measured with the Langmuir probes.

If the bulk of the electric field activity was caused by dust particle impacts⁵, then the spectrum of random electric pulses induced by dust particles should decrease monotonically with increasing frequency, F , as $F^{-\alpha}$, with $1 \leq \alpha \leq 2$. In order to investigate whether waves of some other origin are also present, we have analysed noise spectra obtained near the comet (Fig. 2). One spectral maximum was found, at 200–400 Hz; its interpretation awaits comparison with the results of other experiments.

Langmuir probes are generally used in the dense plasma of planetary ionospheres, and the present aim was to apply this technique inside the cometary coma. The probes were operated in the solar wind during the interplanetary transit; as expected, their behaviour here was influenced by photoemission. Under the bombardment of solar photons, the spacecraft and probe

surfaces emit electrons, some of which orbit back to the spacecraft and some of which escape into the environment. This photoelectron cloud has a density of $\sim 100 \text{ cm}^{-3}$ at the location of the Langmuir probes and masks the solar-wind plasma which is much more rarefied.

On entering the coma, the cometary plasma electron current collected by the probe increases and is detected when it becomes comparable to the photoelectron contribution. In practice, it is difficult to detect ambient plasma of density $< 50 \text{ cm}^{-3}$. Figure 3 shows density profiles obtained with the probes on Vega 1 and Vega 2, as a function of distance to the nucleus. The probe potential was swept between -6 and $+6$ V on Vega 1 and between -4 and $+2$ V on Vega 2. These profiles are based on the analysis of a limited number of voltage sweeps and the spatial resolution can be improved in later treatments.

The observed increases, starting at 3×10^5 km for Vega 1 and 1.5×10^5 km for Vega 2, are undoubtedly associated with the cometary environment. Plasma production was significantly less during the Vega 2 fly-by: this difference appears over a large distance scale, and is likely to reflect a difference in overall coma plasma density between the two fly-by times.

The highest plasma density measured by Vega 1 was $\sim 4,000 \text{ cm}^{-3}$ at 3×10^4 km, before the failure of the instrument; the electron temperature was then estimated to be ~ 1.5 eV. The Vega 2 Langmuir probe gave good data until 6.5×10^4 km, at which time the plasma density was $1,000 \text{ cm}^{-3}$. Data from distances $< 6.5 \times 10^4$ km require further processing.

It was expected that the Langmuir probes would be influenced by secondary electron emissions due to gas and dust impact. To minimize this effect, the probes were aligned with the ram direction, with a conical shield to protect their surfaces from gas and dust impacts. This protection obviously worked, because during the encounters no increase in secondary electron emission was observed above the current levels measured in the solar wind.

Confirmation of these preliminary conclusions will require correlation of our results with those of other plasma experiments.

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Extremely-low-frequency plasma waves in the environment of comet Halley

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The low-frequency plasma wave detector (APV-N) carried by the Vega 1 and Vega 2 spacecraft during their encounter with comet Halley registered an enhanced plasma-wave intensity identified with the inbound crossing of a quasi-perpendicular (Vega 1) or quasi-parallel (Vega 2) cometary bow shock. We also describe the characteristics of the plasma waves excited in the process of anomalously fast ionization of the cometary atmosphere in the inner coma.

Due to the negligibly small gravitational field of the comet, its atmosphere expands freely into interplanetary space to distances of millions of kilometres, where it is ionized by solar ultraviolet radiation. The ionized particles of the cometary atmosphere form an ion beam in the solar-wind plasma which relaxes under the action of plasma waves in a range of frequencies from the ion cyclotron to the ion plasma frequency. This process of cometary ion pick-up by the solar wind and the collective interaction of these ions with the plasma flow is specific to the solar-wind interaction with comets. Therefore, in contrast to traditional plasma-wave experiments in planetary projects, the APV-N experiment was designed to make measurements in the extremely-low-frequency (ELF) range in which the cometary plasma-wave frequencies lie. The instrument uses a double Langmuir probe to measure the electric field intensity E , while at the same time measuring plasma ion flux fluctuations with a Faraday cup^{1,2}.

Bow shock processes. The inbound crossing of the cometary bow shock was detected by APV-N on both Vega 1 and Vega 2. On Vega 1, at 03:46 UT, 6 March 1986, when the distance to the cometary nucleus was $\sim 10^6$ km, a sharp increase in plasma-wave intensity up to a few millivolts per metre was observed at the lowest frequencies analysed by APV-N; that is, at frequencies characteristic of quasi-perpendicular shocks. Figure 1A shows sample records of the intensity of fluctuations in ion flux (a) and electric field strength (b, c) during the Vega 1 bow shock crossing. The crossing (marked by an arrow) is also revealed by the change of incidence angle of the incoming plasma flow detected by the multi-collector Faraday cup of APV-N. The spectrum and frequencies of these waves are similar to those observed upstream of the Earth's bow shock^{3,4}; therefore, we may conclude that these are high-frequency magnetosonic waves excited by an ion beam. However, this beam is formed here not by plasma ions reflected from the shock front but by cometary ions that leak forward from behind the shock front and are accelerated in the self-consistent electric field of the plasma flow⁵. These accelerated ions add a bunched ion beam to the otherwise smooth, ring-type distribution of ions in velocity space. The measured thickness of the shock front ($\sim 10^4$ km) is of the order of the cometary ion Larmor radius, as expected.

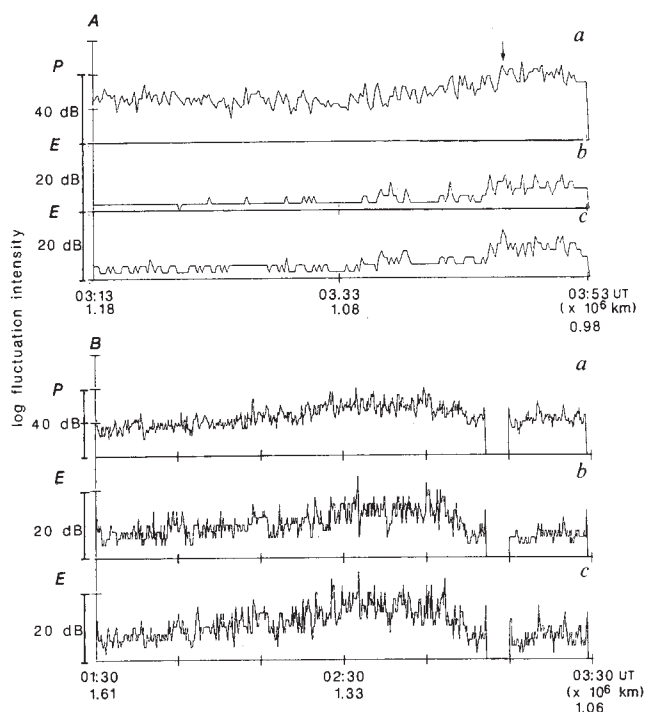


Fig. 1 Fluctuations in ion flux (a , 1.5 Hz) and electric field intensity (b , 3.5 Hz; c , 1.5 Hz) in the solar wind during the Vega 1 (A) and Vega 2 (B) bow shock crossings. Spectral measurements were performed at 15 fixed frequencies (for ion flux P and electric field intensity E): 1.5K, 3.5K, 5.5K, 7.5K and 9.5K, where $K = 1, 10$ and 100 Hz, with bandwidth $\Delta f = \pm 0.8K$. The time interval between measurements of spectra is 12 s and the signal collection time is $(8/K)$ s. Universal Time and distance to the cometary nucleus are given on the horizontal axis. The gap in the data in b is due to a changeover between telemetry modes.

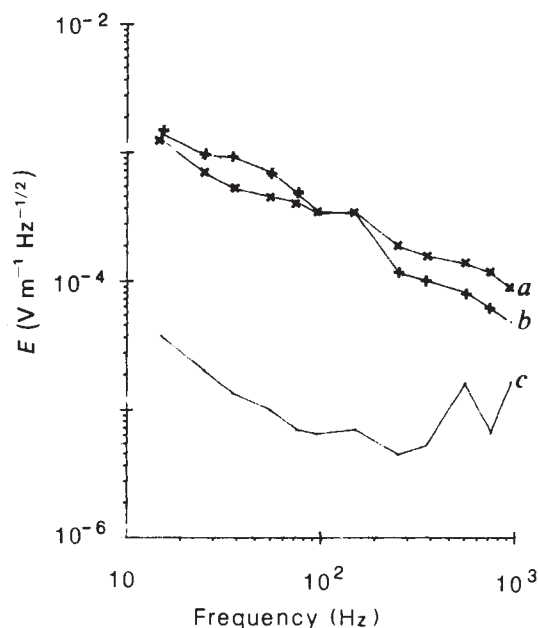


Fig. 2 Plasma-wave spectra measured by Vega 2, strongly influenced by dust impacts. a , Spectrum recorded at 07:19 UT. b , Spectrum recorded at 07:10:54 UT, representing the high-frequency extension of the spectra in Fig. 3 obtained from waveform measurements. Curve c indicates the noise level. Spectral measurements were performed at 1-s intervals in the same manner as described in Fig. 1 legend, with $K = 10$ and 100 Hz; however, the spectra displayed here are 20-s averages.

The structure of the bow shock registered by the Vega 2 APV-N (Fig. 1B) is significantly different from that described above. First, there is no sharp increase in wave intensity. The shock is identified only as a region of well-developed turbulence in the plasma flow, characterized by a significant increase in plasma particle flux oscillations at a frequency of 1.5 Hz (Fig. 1B, spectrum *a*). The intensity of the electric field oscillations here exceeded 1 mV m^{-1} . The decrease in wave activity at the end of the interval shown in Fig. 1B is evidence of the entry of the spacecraft into the region behind the shock. The general behaviour of the plasma waves is characteristic of a quasi-parallel shock located at a distance of $1.1\text{--}1.3 \times 10^6 \text{ km}$ from the nucleus, with multiple transitions occurring between unperturbed and perturbed plasma flow. These transitions are accompanied by jumps of the quasi-steady electric field intensity, of amplitude $\sim 1\text{--}3 \text{ mV m}^{-1}$. The main mechanism of energy dissipation in the quasi-parallel cometary bow shock is probably related to the anomalous heat conduction of cometary ions, reduced by the scattering of ions by excited Alfvén waves; the shock structure is probably similar to that of a cosmic ray shock⁶. The position of both bow shock crossings is consistent with theoretical estimates, if one uses the solar-wind parameters and gas production rate measured by the Vega PLASMAG instruments⁷.

In the region of solar-wind flow behind the shock, the signal recorded by the plasma-wave detector is most pronounced when nitrogen is continuously released from the infrared spectrometer cooling system, and during the 2-h interval surrounding closest approach to the nucleus, when dust particle impacts on the electric field sensors and other parts of the spacecraft strongly influence the wave measurements. Bursts of wave emission in the frequency range 15–55 Hz, possibly caused by mass loading, are frequently seen above the high noise level caused by dust impacts. This noise is very similar to that observed during the ICE (International Cometary Explorer) encounter with comet Giacobini-Zinner⁸ (Fig. 2).

Inner coma processes. During the passage of Vega 2 through the inner coma the PLASMAG instrument registered a rather rapid increase in cometary plasma density at a distance of $\sim 40,000 \text{ km}$ from the nucleus, accompanied by large fluxes of suprathermal electrons with energies of up to a few keV (ref. 7). The plasma density build-up time ($\sim 30 \text{ s}$) is here much smaller than the photoionization time, so this density increase may be explained only by the possible occurrence of the critical ionization velocity phenomenon⁹, for which the plasma mechanism was considered in ref. 10. This phenomenon arises from the collisionless transfer of kinetic energy from newly born cometary ions in the plasma to suprathermal electrons, by means of plasma waves. Figure 3 shows the plasma-wave spectrum recorded at the time of the density increase observed by PLASMAG (together with spectra recorded 30 s earlier and 20 s later); a pronounced peak at 15 Hz with amplitude $E \approx 7 \text{ mV m}^{-1} \text{ Hz}^{-1/2}$ can be seen above the dust-impact noise. As expected from the theory of anomalous ionization¹⁰, the frequency of these waves is of the order of the lower hybrid resonance frequency in cometary plasma, calculated for the measured field $B = 50 \text{ nT}$ (ref. 11).

For finite β_i (the ratio of solar-wind ion pressure to magnetic field pressure), the high-frequency magnetosonic waves propagating across magnetic field lines are strongly damped. At the same time, the temperature of thermal electrons is expected to be so low due to radiation losses in the dense cometary gas that $\beta_e \ll 1$. In this case, oblique Langmuir waves (which become whistler-mode waves in a finite- β_e plasma) can propagate in the plasma with frequency⁴

$$\omega = \omega_{ce}(k_{\parallel}/k)/(1 + \omega_{pe}^2/k^2 c^2) > k_{\parallel} v_{Te} \quad (1)$$

where k and $k_{\parallel}$ are the wave vector and its component along the magnetic field direction, ω_{pe} is the electron Langmuir (or plasma) frequency, ω_{ce} is the electron gyrofrequency, c is the

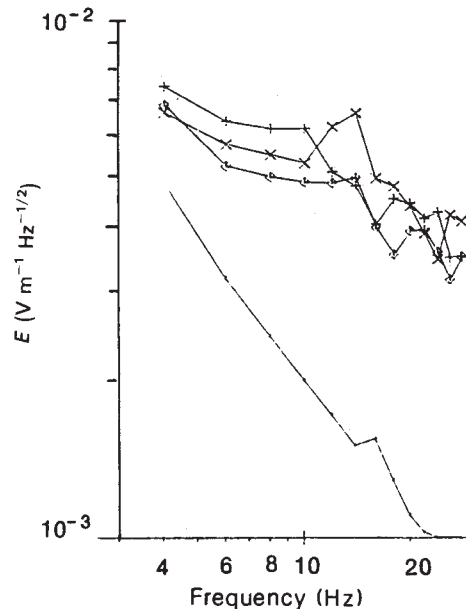


Fig. 3 Fourier spectra of a.c. waveform data from a 20-s interval with sampling rate 64 Hz, measured by Vega 2 30 s before (+), during (x) and 20 s after (◇) the abrupt increase in plasma density observed by the PLASMAG instrument⁷ at 07:11:40 UT, 9 March 1986. The lowest curve is the noise level for this channel. Some of the differences between these spectra and those from the on-board analyser (Fig. 2) are due to the width of the on-board spectral window, $\Delta f = 16 \text{ Hz}$ for frequencies 15–95 Hz, so that the spectral density shown in Fig. 2 is obtained by dividing the output filter signal by $\sqrt{\Delta f}$, and may therefore differ by as much as a factor of 4 from the narrow-band spectral density.

speed of light and v_{Te} is the electron thermal velocity. The minimum damping of these waves occurs when $k \approx \omega_{pe}/c$; therefore, the frequency of waves excited by the beam of newly born cometary ions gyrating with the local plasma velocity u can be estimated as $f \approx ku/2\pi$. For calculated plasma density $n_e \approx 300 \text{ cm}^{-3}$ and velocity $u \approx 30 \text{ km s}^{-1}$ (ref. 12) we obtain $f \approx 15 \text{ Hz}$, consistent with our measurements. The intensity of excited plasma waves can be estimated from the condition that the time for quasi-linear relaxation of the cometary ion velocity distribution to the more stable distribution is of the order of the characteristic time of ionization by electron impact¹⁰. This estimate, for the assumed plasma parameters, gives $E \approx 1\text{--}3 \text{ mV m}^{-1} \text{ Hz}^{-1/2}$, consistent with our measurements. We note that the Townsend condition for a self-sustained high-frequency discharge given in ref. 10 is satisfied in this region of the coma. In addition, reconsideration of the energy transfer efficiency η for the case of flow continuously decelerating under the action of mass loading¹³ gives $\eta = 0.15$, resulting in a reasonable value for the critical velocity, $v_{cr} \approx 30 \text{ km s}^{-1}$.

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The Planet-A Halley encounters

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Two spacecraft, Sakigake and Suisei, were launched in the Japanese Halley mission, the Planet-A project. Both spacecraft accomplished their task successfully. The plasma-wave probe aboard Sakigake, and the ultraviolet imager and the charged particle analyser aboard Suisei, carried out in situ measurements of the cometary environment. This article provides an overview of the project and the results obtained.

WITH the prospect of a visit by comet Halley, the Japanese Institute of Space and Astronautical Science (ISAS) decided to send the Planet-A spacecraft to explore the plasma environment and hydrogen corona of the comet. Such an interplanetary mission was a new experience for ISAS. An engineering test spacecraft, MS-T5, was also dedicated by ISAS to the study of Halley after necessary engineering tests had been carried out, and designed to carry scientific experiments to study in particular interactions between the solar wind and the comet.

From 1978 the relevant developments have included the upgrading of the Mu launcher, the construction of a new deep space station for telemetry and telecommand and the development of spacecraft for deep space missions.

Launch windows chosen for MS-T5 and Planet-A were January and August 1985, respectively. Following launch, MS-T5 and Planet-A were renamed Sakigake (Japanese for forerunner) and Suisei (Japanese for comet), respectively. All experiments aboard Suisei became operational from September 1985 and all experiments aboard Sakigake were switched on at the end of February.

The spacecraft

Sakigake and Suisei are almost identical except for the scientific experiments they carry. They are cylindrical with a diameter of 140 cm and a height of 70 cm. An off-set parabolic antenna of 70 cm diameter is mounted on top of the cylinder; it has a mechanically de-spinning system. At the bottom, there is a low-gain, cross-dipole antenna and a medium-gain antenna of the co-linear array type. The total height of the spacecraft, including antennas, is ~2.5 m. Around 70% of the outside of the cylinder is covered with solar cells which produce about 100 W during orbit when the spin axis of the spacecraft is kept perpendicular to the ecliptic plane. The spacecraft weighs around 139 kg. To reduce the weight, complex materials such as carbon-reinforced plastic and Kevlar, as well as lightweight materials such as aluminium alloy and titanium are used as structural components. The basic structure consists of a thrust tube and an instrument deck (see Fig. 1), and all instruments are attached to both sides of the deck. There is no protection against cometary dust impacts.

The attitude and velocity control system is composed of a two-hydrazine thruster complex mounted diagonally at the top of the cylindrical body, the thrusting force of each thruster being 3 N. The spacecraft is usually spin-stabilized at a rate of 6 r.p.m., but this can be reduced to 0.2 r.p.m. by means of a momentum wheel when the ultraviolet imager of Suisei is in operation. A Sun sensor and star scanner act as attitude sensors.

A 1-megabit magnetic bubble memory records data obtained during the period of non-contact with the Usuda Deep Space Station.

The thermal-vacuum design of the spacecraft consists basically of a Dewar vessel for the inside, with excess heat being released into space by three thermal louvres, while the outer

surface is partly covered by Kapton film and black paint, and the outer surface of the bottom plate consists of polished aluminium. The inside view of Sakigake is shown in Fig. 2.

Scientific objectives

Because of the strict weight constraints on the spacecraft, it was impossible to carry many experiments and have dust particle protection. Previous work¹ indicated that there are few dust particles at 200,000 km from the comet nucleus on its sunward side, and therefore the first experiment performed by Suisei was measurement of the hydrogen corona seen on the solar hydrogen Lyman- α line. The nucleus of the comet is thought to be composed mainly of water ice which sublimates with other constituents of the nucleus, including dust, and loses weight as it approaches the Sun. Eventually, the comet will lose all volatile material and become inactive. It is therefore interesting to know the total amount of evaporation from the nucleus during one passage in the vicinity of the Sun. Suisei is providing good data on this water sublimation by a routine imaging experiment begun in November 1985 and probably lasting until April 1986. The activity of the comet is also being monitored. Another experiment carried by Suisei measures the number of charged particles in the solar wind as well as in the cometary plasma. Because of the high activity of comet Halley, we considered that it might be possible to detect charged particles of cometary origin at the time of closest approach at a distance of 200,000 km. As Suisei was later manoeuvred so as to approach the comet to within 150,000 km, it seemed even more likely that we would be able to measure the cometary ions, particularly if we took into account the results of the Interplanetary Cometary Explorer

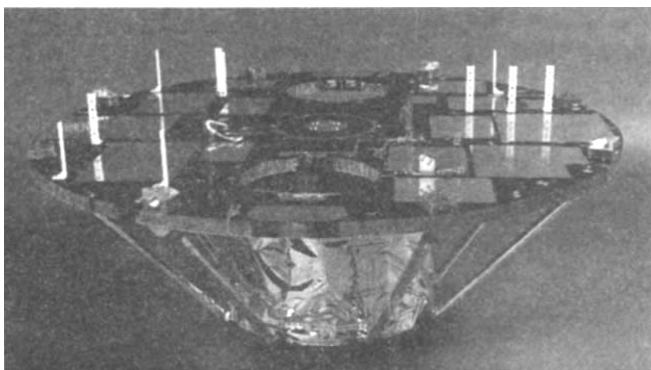


Fig. 1 Basic structure of the spacecraft. Both thrust tube A (diameter 515 mm) and the eight struts that support the instrument deck are made from carbon-fibre-reinforced plastic. The instrument deck has a honeycomb structure, consisting of an aluminium core and titanium plate. Total weight, 13.4 kg. The thrust tube and struts are covered by aluminized Mylar film.

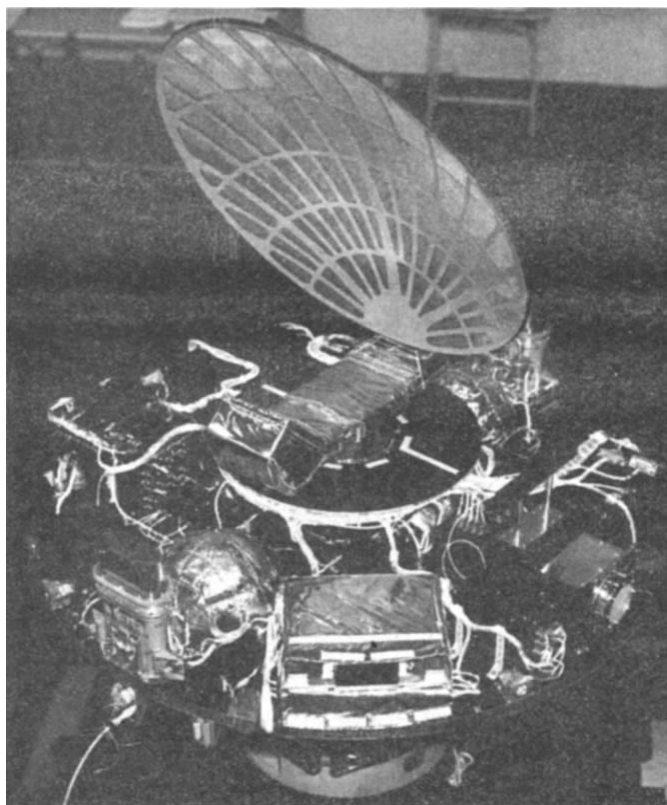


Fig. 2 Inside view of Sakigake with the cylindrical solar cell panel removed. All instruments are attached to both sides of this deck as well as to the thrust tube. Aluminized Mylar film for thermal control is seen around the edge of the deck.

(ICE) spacecraft during its encounter with comet Giacobini-Zinner².

Scientific experiments carried by Sakigake were selected to measure several parameters of the solar wind, bulk velocity, ion density, ion temperature, magnetic field and plasma waves in the low-frequency (LF) and extremely-low-frequency (ELF) ranges. In addition to measuring solar-wind parameters, we also planned to observe the radio emission from the coma region. As is well known, the solar wind interacts strongly with the cometary coma and ion tail, forming a shock front around the coma. Because the penetrating solar-wind particles contribute to ion formation in the coma, while the magnetic field of the solar wind modulates the long ion tail, solar-wind data are essential for analysing the results for the coma and ion tail.

The Inter-Agency Consultative Group, coordinating the four agencies (the European Space Agency, Soviet Intercosmos, ISAS, the US National Aeronautics and Space Administration) and International Halley Watch, asked the Planet-A project group to supply information on the rate of water production by the comet, on jets and outbursts from the nucleus, and on solar-wind conditions at the time of closest approach by the other spacecraft. Although the scientific objectives of the Planet-A project are comparatively limited, coordinated analysis with the results of other spacecraft and ground observations should yield significant contributions to our knowledge of the comet.

Orbits and encounter kinematics

Given the capacity of the launcher, M-3SII, and the weight limitation of the spacecraft as mentioned above, it was impossible to carry a sophisticated attitude control system to facilitate launching from a parking orbit. Both spacecraft had to be launched directly into a heliocentric orbit.

Sakigake and Suisei were launched at 19:26:00 UT on 8 January 1985 and 23:33:00 UT on 18 August 1985, respectively.

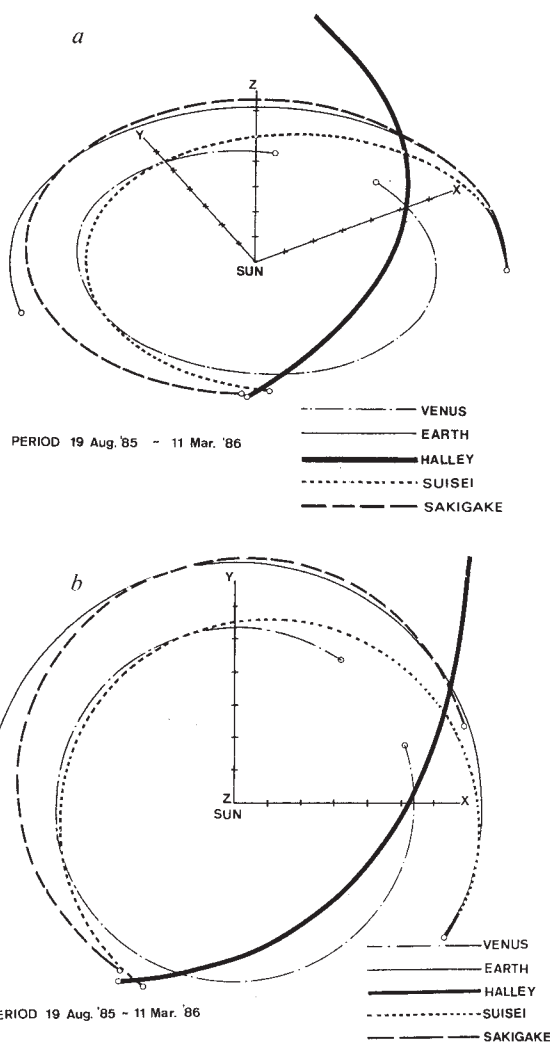


Fig. 3 *a*, A perspective drawing of the orbits of Sakigake, Suisei and comet Halley on 19 August 1985 during the closest approach of Sakigake to the comet. *b*, Projection to the ecliptic plane.

The expected orbits of the spacecraft were 7×10^6 and 200,000 km, respectively, on the Sun side of the cometary nucleus. The launches of the two spacecraft were quite successful and initial distances of 7.6×10^6 and 210,000 km were attained by Sakigake and Suisei, respectively (see Fig. 3). The first orbit correction manoeuvre for Sakigake was carried out 3 days after its launch and the second one on 14 February 1985. The position for closest fly-by was finally fixed at 04:17:51 UT on 11 March 1986, at a distance of 6.99×10^6 km, using the latest ephemeris of the comet. No orbit correction was carried out initially for Suisei, but an orbit correction manoeuvre was subsequently carried out on 14 November and its closest approach was finally fixed at 13:05:49 UT on 8 March 1986 at a distance of 151,000 km from the comet. The encounter geometry is actually three-dimensional, and the paths of Sakigake, Suisei and comet Halley are shown in the *x-y* and *x-z* planes in Fig. 4. The relative velocity between Suisei and the comet is $\sim 73 \text{ km s}^{-1}$.

Results from the Planet-A project

Sakigake and Suisei made successful encounters, and produced satisfactory results in all experiments. As details of each experiment are described in the following articles, only a general overview of the results for each spacecraft will be given here. **Sakigake.** As described above, Sakigake was launched initially as an engineering test spacecraft during the first Japanese

mission into interplanetary space. All the necessary technological tests for deep space communication, attitude determination and correction, and orbital determination and correction for the subsequent spacecraft, Suisei, were successfully completed within 1½ months. The three experiments were then turned on and solar-wind measurements begun.

The solar-wind ion experiment was carried out using a sensor of the Faraday cup type, with four grids and one corrector. It measured the bulk velocity, flow direction, ion density and ion temperature of the solar wind. During the year before the closest approach to the comet, the general structure of the solar wind was fully observed.

The magnetometer experiment consists of three orthogonal components of ring-core type sensors, and has been recording continuously since 19 February 1985, monitoring changes in the configuration of the heliospheric neutral sheet³.

The inferred neutral sheet configuration was used to explain the disturbance in the ion tail of the comet observed on 31 December 1985. The disturbance was observed only in the Asia-Australian zone and although it was similar to the disconnection event reported by Niedner⁴, the comet was too far from the neutral sheet to be affected by it. The Sakigake data suggest that the tail disturbance was caused by the comet impinging on high-velocity solar wind originating from the coronal hole tongue that extends from the northern polar cap ~180° Carrington longitude. On the day of the closest approach of Sakigake, many crossings of the sector boundary were observed. However, no disconnection event was observed during 11–14 March 1986. The Sakigake data suggest that a nearly horizontal undulating neutral sheet passed by the southern side of the comet's ion tail. From the dynamic spectrogram of the observed variation of the magnetic field, the ion cyclotron wave of the ionized water of cometary origin can be presumed to exist even at a distance of 7×10^6 km from the nucleus.

The last experiment, the plasma-wave probe, found many traces of a rising and falling tone type of emission in its LF band (30–195 kHz)⁵. The physical interpretation of these emissions is unclear, but they are probably the plasma wave stimulated by shock waves travelling through the cometary coma. Instabilities giving intense electrostatic waves associated with the ion pick-up phenomena have also been observed in the ELF and LF ranges. By taking the simultaneously observed solar-wind velocity into account, the shock is considered to approach to within 400,000–500,000 km of the cometary nucleus, where the solar wind interacts with the coma. Sakigake carried out as many solar-wind measurements as possible in order to define the environmental conditions at the time of closest approach of the other spacecraft. At the time of closest approach of Giotto, it served as the reference spacecraft to eliminate atmospheric and ionospheric effects in Giotto's radio experiment.

Suisei. This spacecraft carried two experiments, an ultraviolet imager for observing the hydrogen corona around the cometary coma and a charged-particle energy analyser to observe the solar wind and cometary ions. However, these two experiments were carried out at different times, because they needed more information bits than the capacity of the spacecraft telemetry allowed and also different spin rates. Therefore, the two experiments had to alternate their observation time.

As Suisei was launched so accurately into its expected orbit, the first orbital correction manoeuvre was not necessary, and the ultraviolet imager was turned on from the beginning of September 1985, just before the closest approach of comet Giacobini-Zinner by the ICE spacecraft. The imager was first tested by taking ultraviolet pictures of the Earth which were of reasonable size and brightness. Many images of O- and B-type stars were also obtained, suggesting wide-band emission in the ultraviolet range from these stars. After these tests, trial imaging of comet Giacobini-Zinner was carried out, but no good image was obtained at the time of closest approach of the ICE space-

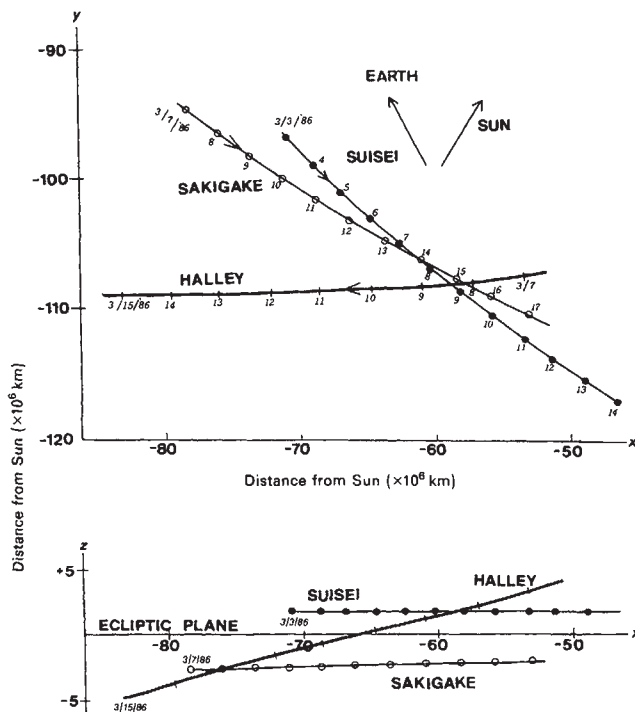


Fig. 4 Three-dimensional display of the encounter geometry.

craft to the comet, although faint images of the comet were obtained several days later.

From the middle of November, when the comet Halley was 2.5×10^8 km from the Sun, the imager began to detect the hydrogen corona around the comet. Observations over a week or so revealed that the brightness of the hydrogen corona was changing from day to day.

From observations made between 26 November 1985 and 13 December 1985, the brightness change was quite regular, with a period of 2.2 ± 0.1 days (ref. 6), which is interpreted in terms of the spin period of the cometary nucleus. Also, the hydrogen corona was found to have a shell structure. The imaging experiment was continued until 10 January 1986, when the comet approached too close to the Sun, and the separation angle between the Sun and the comet became so small that the functioning of the imager's optical system was impaired. However, imaging returned on 9 February 1986, when the comet reached perihelion. The mean brightness of the hydrogen corona increased at the beginning of March 1986, with active breathing⁷. This is quite an interesting result, as it suggests that the surface of the nucleus of this relatively 'old' comet may be different from that of a young comet. Imaging will probably be continued until the end of April of this year, by which time the hydrogen corona will have become too faint to be detected by the imager. The total amount of water evaporated from the nucleus can then be estimated.

At the time of closest approach, the operation mode of the imager was changed from normal imaging mode to the so-called photometry mode, in which histograms of brightness of each image frame were sent to the ground station. This was because, inside the hydrogen corona, the imaging target is so wide that a few images cannot recover much information on the coronal structure, as the rate of information is only around 64 bits per s and the capacity of the spacecraft's magnetic bubble memory only 1 Mbit. With the imager in the photometry mode, the imaging field was fixed relative to the direction of the Sun so that the field of view contained no ultraviolet stars. The photometry mode was operated for 2 days before the closest approach and was turned off just before the closest approach to give preference to the experiment analysing the energy of the charged

particles. During operation of the photometry mode the radial distribution of the density of hydrogen inside the corona was obtained and was found to be roughly inversely proportional to the square of the radial distance from the nucleus, although several structures were also observed.

The charged particle experiment began to observe the solar wind on 27 September 1985, and several characteristics of the solar wind were obtained. The experiment was begun just before the closest approach, at a distance of 200,000 km, and the characteristics of the particles observed were found to be completely different from those observed until then. However, the original features of the solar wind feature reappeared after Suisei had travelled to within $\sim 420,000$ km of the nucleus. A detailed description of this is given elsewhere⁸, but it may be said that Suisei detected real cometary ions. It is not surprising that the proton is still the main ion in this region, and using this assumption, we conclude that the flow velocity of the solar wind is reduced to around 70 km s^{-1} , one-fifth of its velocity in the outer region, and that the direction of flow is also quite disturbed, just like the flow at the front of any obstacle. The boundary observed at $\sim 420,000$ km shows an abrupt change, suggesting the existence of a region of interaction between the solar wind and the inner coma of the comet. By combining this result with that of the plasma-wave probe aboard Sakigake, the thickness of the interaction region can be presumed to be around

200,000 km. Observed ions were also identified as ions of water, carbon monoxide and carbon dioxide.

Finally, we should mention that on two occasions during the time of closest approach Suisei was hit by large dust particles, estimated to weigh several milligrams. Such particle impact data should contribute to the modelling of millimetre- or sub-millimetre-size dust around the comet.

The planet-A project is financially supported by the Ministry of Education, Science and Culture, for which we are extremely grateful. The project was conducted by the staff and members of the Institute of Space and Astronautical Science, supervised by the Director-General Dr M. Oda. Part of the tracking and data acquisition were greatly helped by NASA, particularly the Jet Propulsion Laboratory, NASA. On behalf of the project team, we express our thanks to these organizations. Tracking support from NASDA during the initial phase is also appreciated.

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Observation of comet Halley by the ultraviolet imager of Suisei

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The ultraviolet imager aboard the Suisei spacecraft recorded the variation with time of the Lyman- α intensity of the coma of comet Halley. Strong breathing was still occurring at the hottest phase of the apparition, in the same pattern as was observed in November–December 1985 (ref. 1). This observation confirms that the nuclear surface of Halley is largely covered with a hard substance. The observed periodicity may affect near-nucleus phenomena of the cometary ion tail. It was further found that two strong sources and at least four weak sources contribute to the above periodic breathing; most of the sources fall on two-thirds of each cycle of activity. At the time of encounter of Suisei with comet Halley, the Lyman- α brightness data were obtained for the first time within the thick hydrogen coma. The photometry data follow fairly closely the theoretical curve that took into account the effect of the periodic outbursts.

In the early phase of Suisei's approach we found strong breathing of the hydrogen coma of comet Halley¹. The breathing overwhelmed other activities such as continuous sublimation from the whole surface. If the breathing is caused by an outburst (or jet) from nuclear surface features (fractures or holes) that are activated when rotation of the nucleus brings it into a position where it is illuminated by the Sun, the repetition of breathing activity throughout this apparition would suggest that the major portion of the nuclear surface is covered by a hard substance. This outburst activity can be measured directly by examining the distribution of the hydrogen atom density at the

time when Suisei penetrated the coma.

The ultraviolet imager carried by Suisei (E.K., M.T. and K.H., in preparation) is controlled by commands from the Earth, either direct or programmed (the latter are quite useful because they can direct a series of observations at pre-set times and positions). The imager also automatically protects itself from bright sunlight. This imager (effective field of view, $1.85^\circ \times 1.96^\circ$), using a charge-coupled device (CCD) area sensor, produces a digital image composed of 122×153 pixels, the light level of which is represented by 8 bits. Successive images can be obtained every 5 (or even 10) min. The instrument has two observational modes: an imaging mode and a photometry mode. The latter mode transforms the image data into a histogram of the light-level distribution for all pixels. The memory required for data storage for each image is greatly reduced in the photometry mode (512 compared with 18,666 bytes for the imaging mode), which is important for some observations, given the limited capacity of the onboard magnetic bubble recorder ($\sim 1 \times 10^6$ bits).

The images of the hydrogen coma of comet Halley have been recorded since 26 November up to the present, except for the period 11 January to 8 February, when the elongation angle of the comet precluded observation. At specific times during, and a few days before the encounter, data were obtained in the photometry mode. Throughout the observation period the total brightness of the hydrogen coma was changing rhythmically (or periodically if we neglect a minor systematic shift of the period due to change in the relative positions of the Sun, comet and spacecraft). Figure 1 illustrates the variation in the Lyman- α intensity; an image obtained during a bright phase ($\sim 11:00$ 28 February UT) is shown alongside an image obtained at a dark phase ($\sim 13:00$ 25 February UT). As the rate of gas production was predicted to be highest on 3 March, during the post-perihelion phase², the bright image shown is one of the brightest obtainable for this apparition. For comparison, Fig. 2 shows bright- and dark-phase images obtained in the middle of December.

That periodic activity continued during the most active phase of the present apparition as well as in its earlier phase, confirms previous suggestions that the surface of the nucleus of comet Halley is covered with a hard (reddish-black³) substance, except for some water-jet sources such as fractures or holes. Television images⁴ of the surroundings of the nucleus taken by Vega 1 and Vega 2 showed asymmetric features, suggesting jet activity from

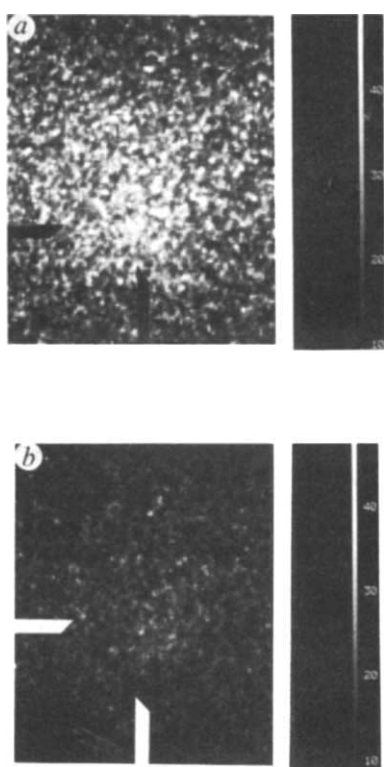


Fig. 1 Lyman- α images of the hydrogen coma of comet Halley, taken at *a*, 01:00 UT on 28 February 1986 (bright phase) and *b*, 13:00 UT on 25 February 1986 (dark phase). The vertical and horizontal dimensions of the photographs are: *a*, 1.5×10^6 km and *b*, 2.0×10^6 km. The comet nucleus (located at the intersection of the black marker wedges) is at $((\alpha_0, \delta_0) = (12 \text{ h } 54 \text{ min}, 2^\circ 27' \text{ N})$ in *a* and $(22 \text{ h } 54 \text{ min}, 2^\circ 33' \text{ N})$ in *b* (1950.0 star atlas coordinates). The distances of the comet from the Sun and Susei are: *a*, 0.717 and 0.339 AU and *b*, 0.684 and 0.459 AU, respectively. The reference scale on the right side of each image indicates relative brightness. Extracometary contributions from the interplanetary Lyman- α glow, instrumental dark current and stray sunlight scattered from a guide mirror surface total ~ 14 –15 on this scale.

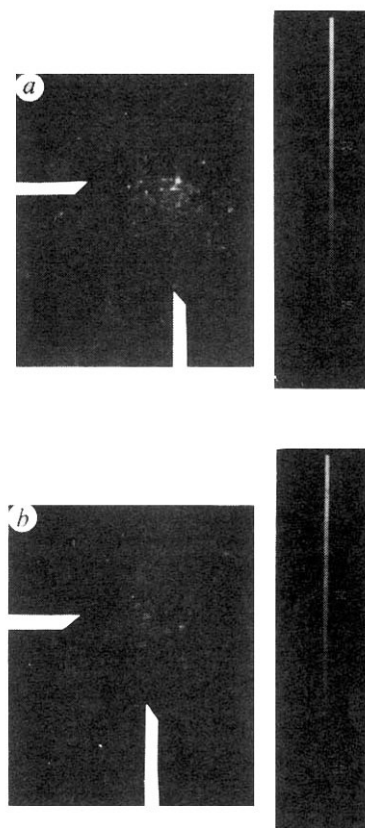


Fig. 2 Lyman- α images of the hydrogen coma of comet Halley. *a*, 23:00 12 December 1985 UT; dimension 4.0×10^6 km; position (0 h 25 min, $9^\circ 28' \text{ N}$); distances from Sun and Susei, 1.301 and 1.006 AU. *b*, 02:00 11 December 1985 UT; 4.0×10^6 km; (0 h 33 min, $10^\circ 13' \text{ N}$); 1.330 and 0.976 AU. Each image was obtained by superposing five images taken at 10-min intervals; therefore, actual brightnesses are one-fifth of those shown. The extracometary contributions lie, on this reduced brightness scale, at ~ 3 –4. The stray sunlight is negligible in these images.

the nucleus. Giotto images⁵ taken in the 4 h before closest approach also showed that jets are the main form of cometary activity, at least in this period. It is quite remarkable that the nucleus was active only on the sunlit side.

The above periodic activity suggests strongly that some plasma tail phenomena, such as disconnection found near the nucleus, could be interpreted in terms of variation in ion density in the ionosphere of comet Halley, occurring in response to the neutral-density variation in the inner coma that was clearly observed in our experiment. This conclusion does not necessarily exclude the possibility of a hydromagnetic interpretation of tail disturbance phenomena far away from the nucleus.

After the encounter, Lyman- α imaging of comet Halley was resumed in mid-March. As these images were less bright than those obtained during the hottest phase, the flashes in the vicinity of the nucleus that we reported earlier were again detectable (at $\sim 06:00$ 18 March, $\sim 10:00$ 20 March, $\sim 21:00$ 24 March and $\sim 01:00$ 27 March UT), confirming the rotational period of 2.2 days. We also used the photometry (histogram) mode from $\sim 03:00$ 21 March to $\sim 13:00$ 23 March UT (58-h continuous period) to determine the positions of outburst sources in one rotational period. The analysis suggests the presence of two strong sources (S_1 and S_2) and four weaker sources (W_1 , W_2 , W_3 and W_4) on the surface of the nucleus, confirming the results of a number of other images. If we take as the origin the time of onset of the strongest source S_1 (which is accompanied by a weak source W_1 after a delay of 3 h), another strong source, S_2 , occurs at 22 h. Further weak sources, W_2 , W_3 and W_4 , occur at ~ 11 , 30 and 48 h, respectively. In the time interval between 33 and 53 h, cometary activity is much quieter than in the active interval between 0 and 33 h (see Fig. 3).

Extrapolating the above result to the other Halley spacecraft, Vega 1 appears to have reached closest approach 7 h after the onset of S_2 , thus directly experiencing this outburst (if we assume the velocities of gas and dust in outbursts to be $\sim 300 \text{ m s}^{-1}$).

On the other hand, the closest approach of Vega 2 occurred just before the onset of S_1 , thus experiencing a weak source W_4 . The fact that the measured gas and dust densities at the time of the Vega 1 closest approach were about twice those at the time of the Vega 2 closest approach appears to reflect this situation. Giotto passed by the comet 4 h after the S_1 outburst and 1 h after the W_1 outburst; these outbursts may have had a severe effect on this spacecraft. Susei seems to have reached closest approach after the outburst of W_3 had occurred.

We obtained some Lyman- α images of the Earth on 7 September, when Susei was about 5×10^6 km from the Earth. By fitting these images to the Lyman- α image of the Earth taken by Apollo 16 (ref. 6), we can roughly calibrate the present ultraviolet imager, as both observations were made under similar conditions of solar activity. We have already prepared a detailed computer program to calculate contour maps of the hydrogen coma of comet Halley at any spacecraft configuration. This theoretical model cannot, however, be used to determine directly the rate of water production of the comet, as the observed intensity variation suggested that the activity of the outburst must be taken into account in model-building. Such a modification of the program is in progress. We expect, however, that a rough estimate of the rate of water production (in particular its relative value) is still possible using the theoretical mode. Such a comparison indicates that the rate of water production may vary by about a factor of three between the brightest and faintest phases.

Over 8 h before the closest approach to comet Halley, successful observations were made in the photometry mode, with the ultraviolet imager pointed in a constant direction ($\alpha_0, \delta_0 = 11 \text{ h } 20 \text{ min}, 5^\circ \text{ S}$). In Fig. 4, relative values of Lyman- α intensity are plotted as a function of universal time. As already mentioned, it is now clear that the hydrogen coma is highly variable. We have developed the following non-stationary model to calculate the hydrogen density distribution of the coma for a water production rate exhibiting outburst-type variability.

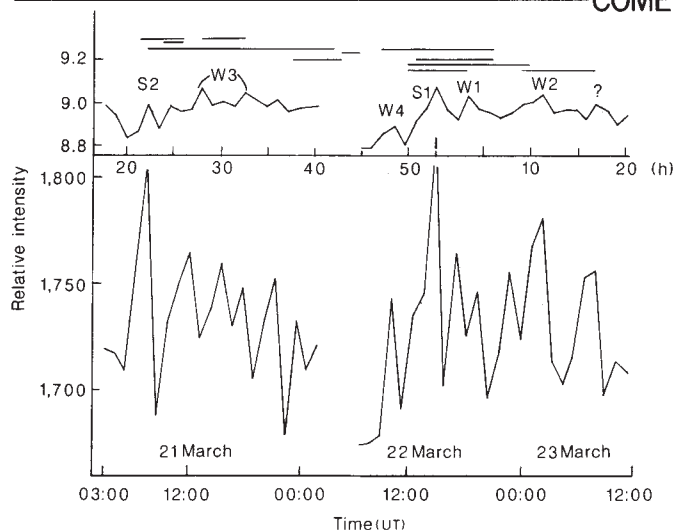


Fig. 3 Occurrence diagram of outburst sources. The upper curve shows the time variation of the Lyman- α intensity averaged over all pixels in the photometry histogram obtained from ~03:00 21 March to ~13:00 23 March UT with a 68.33-min interval; the lower curve sums the intensities from the 100 brightest pixels. Times on the upper abscissa are counted from the S_1 source and those on the lower abscissa are shown in universal time. The gap in the centre of the curves (around 03:00 22 March) was caused by the reset of the solar elongation, which puts comet Halley back into a proper position of the field of view. Six sources are identifiable (see text) and are further confirmed by the images taken at their occurrences in later cycles. Bars at the top of the figure show these time intervals; for some of the sources the imaging was repeated several times, enabling us to confirm the rotational period of the nucleus, 53 h. The source marked '?' was not confirmed, since the brightness of the comet had decreased before we could apply this method.

The jet is modelled as a point source of periodically outbursting water molecules with a constant rate during the first 33 h, after which there is an interval of 20 h in which no outbursting occurs; this approximates to our observations. H_2O and OH , the parent molecules of H , are assumed to be localized at the origin because of the negligible outflow velocity of these parent molecules compared with those of photofragmented hydrogen atoms. Production rates for the hydrogen atom, $Q(t)$, are computed by taking into account the finite disintegration times of H_2O and OH : 1.1 and 2.3 days, respectively, at 1 AU. Using this rate, the atomic hydrogen density for the high-velocity ($v = 20 \text{ km s}^{-1}$) component from H_2O is calculated as

$$n(t, r) = \frac{Q_{H(H_2O)}(t - r/v)}{4\pi r^2 v} e^{-r/\tau v}$$

where τ is the lifetime of atomic hydrogen and r is the radial distance from the nucleus. A similar expression can be obtained for the low-velocity ($v = 8 \text{ km s}^{-1}$) component from OH . The data for 8 March follow the theoretical curve fairly closely (see Fig. 4). Our numerous test calculations show that an isolated single jet event does not satisfactorily explain either the spatial distribution of the observed Lyman- α intensity, or features varying with time. Figure 4 illustrates that repeated jet events yield the spatial intensity distribution expected from continuous evaporation of water molecules. For comparison, Fig. 4 also shows the variation of Lyman- α intensity based on the classical Haser model.

The data plotted in Fig. 4 reveal a certain amount of fine structure when examined in detail. These features have also been observed in some Lyman- α images taken before and after the encounter, and suggest the existence of a ring (or shell). Such structures are quite narrow and could not be ascribed to hydrogen derived from water, but to hydrogen from other (organic) substances. A detailed analysis will be presented in future.

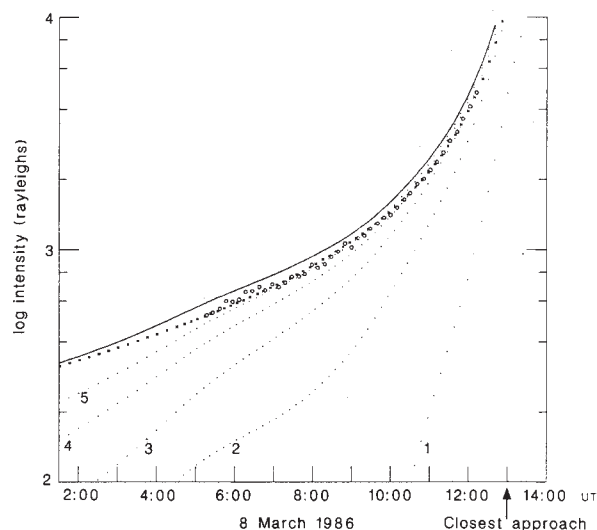


Fig. 4 Lyman- α intensity recorded by Suisei, plotted on a relative scale (open circles). The dotted curves labelled 1-5 represent the intensity for outbursts repeated one to five times, respectively. The adopted outburst parameters are as follows: period, 53 h; latest onset time before encounter, 20 h; outburst duration time, 33 h. The asterisks denote the intensity obtained from Haser's hydrogen density distribution for the water production rate proposed by Divine *et al.*². The corresponding rate for an outburst considered here is given so that both rates become equal when averaged over a long time. During our observation period, the field of view of the imager was pointed in the direction $(\alpha_0, \delta_0) = (11 \text{ h } 20 \text{ min}, 5^\circ \text{ S})$. The heliocentric distance of the comet at the time of closest approach (13:06 8 March UT) is 0.823 AU and the distance of the comet from Suisei is 151,000 km.

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Plasma observation by Suisei of solar-wind interaction with comet Halley

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The Suisei probe¹ made a closest approach of 151,000 km to comet Halley at 13:06 UT on 6 March 1986, and during the encounter Suisei passed through a strong interaction region, where the solar-wind flow was severely perturbed by picked-up ions of cometary origin. Plasma observations from Suisei clearly demonstrate the existence of the assimilation process of cometary ions in the solar-wind flow. Within $2.3 \times 10^5 \text{ km}$ of the cometary nucleus, shell structures in the velocity space of cometary protons and water-

group ions were clearly seen. Other ions, such as CO^+ (and/or N_2^+) and CH^+ (and/or C^+), were also identified from the E/q spectrum. An abrupt change of the plasma parameter was detected around 4.5×10^5 km away from the nucleus, which probably represents the bow-wave crossing. The mass-loading effect was observed at a distance of up to $\sim 1 \times 10^6$ km.

Because of the weak gravitational force of comets, neutral gas sublimated from the nucleus can escape freely from the collision-dominated inner coma. Neutral molecules in the comet are eventually ionized through processes² such as photoionization by solar extreme-ultraviolet photons, charge exchange with solar-wind protons, collisional ionization by energetic electrons, and possibly Alfvén's critical ionization mechanism. The cometary ions then begin to rotate around the solar-wind magnetic field and form a torus in velocity space. Since such a torus is unstable to various instability processes, these ions are subjected to pitch-angle scattering and/or energy scattering processes, the details of which critically depend on the microscopic (assimilation) process involved.

As cometary ions are added, the solar-wind flow is slowed down by the mass-loading process, which may also influence conditions for bow-shock formation. Evaluations of the effect of mass-loading on the shock condition have ranged from a negligible contribution³ to severe weakening of shock strength⁴. **Instrumentation and data handling.** The three-dimensional plasma instrument (ESP instrument: energy spectrum of particles) on Suisui consists of three main parts: a fan-shaped collimator, a 270° -spherical electrostatic analyser and a microchannel plate^{5,6}. Because of telemetry constraints, however, the ESP instrument was operated in the two-dimensional mode during the encounter with Halley. The field of view is $5^\circ \times 60^\circ$, with the longer dimension being perpendicular to the ecliptic plane. The geometric factor ($(S\Omega\Delta E)/E$) is $2.3 \times 10^{-4} \text{ cm}^2 \text{ sr}$. The energy range from 30 eV/ q to 15.8 keV/ q (where q is the charge state) is divided into 96 steps, equally spaced on a logarithmic scale. During one spin period (9.18 s), ion fluxes in four successive energy steps are measured in 22 azimuthal sectors, where the width of one sector is 5.625° within $\pm 22.5^\circ$ from the solar direction and is 22.5° outside. The energy scan is made alternatively every 16-spin period (147 s) for the lower 64 steps (30 eV/ q –1.92 keV/ q ; scan mode 'L') or for the higher 64 steps (248 eV/ q –15.8 keV/ q ; scan mode 'H'). Because the downlink telemetry requires 512 s to send one sample of the distribution function (in 64 steps $\times$ 22 sectors), there were 365-s observation gaps between samples.

From the sampled distribution functions, plasma parameters are calculated by three methods: (1) a fitting algorithm for shifted bi-maxwellian distribution, which is usually used in the solar-wind plasma, (2) a fitting algorithm for the shell-like distribution characteristic of the cometary plasma assimilation process, and (3) an algorithm to take the moment of the sampled distribution within some specified range of energy and direction. In any of these methods, errors in determining the proton flow parameters (the density, in particular) become large if the flow speed is slower than $\sim 80 \text{ km s}^{-1}$ in the spacecraft frame, since the large part ($> 50\%$) of the proton distribution falls below the instrument coverage (below 30 eV).

The relative velocity of comet Halley with respect to Suisui, V_{HC} , was $(-18, 70, -12) \text{ km s}^{-1}$ during the encounter. (To represent velocity components, we shall use a cometocentric solar coordinate system, where the x axis is taken in the ecliptic plane towards the Sun, the y axis towards the east, and the z axis towards north.) In the following analysis, we assume that the plasma flow was within the ecliptic plane. This is a reasonable assumption in the upstream solar-wind region and within the cometary ionosphere. (The geometry of Suisui's orbit with respect to comet Halley means that the refracted solar-wind flow at Suisui is likely to be within about $\pm 10^\circ$ from the ecliptic plane, but if the flow direction is as large as 30° out of the ecliptic plane, the following velocity estimation would have an

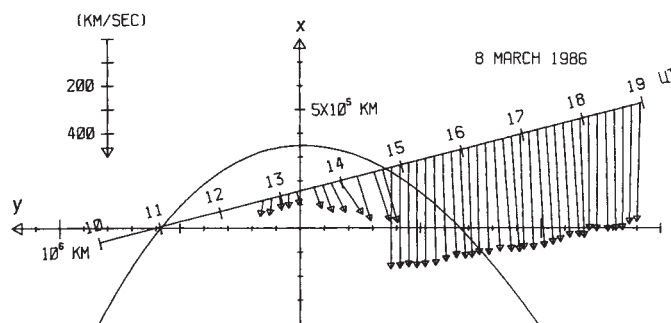


Fig. 1 Plasma flow vectors obtained during Suisui's encounter with comet Halley. The flow vectors and angles are represented in the rest frame of the comet.

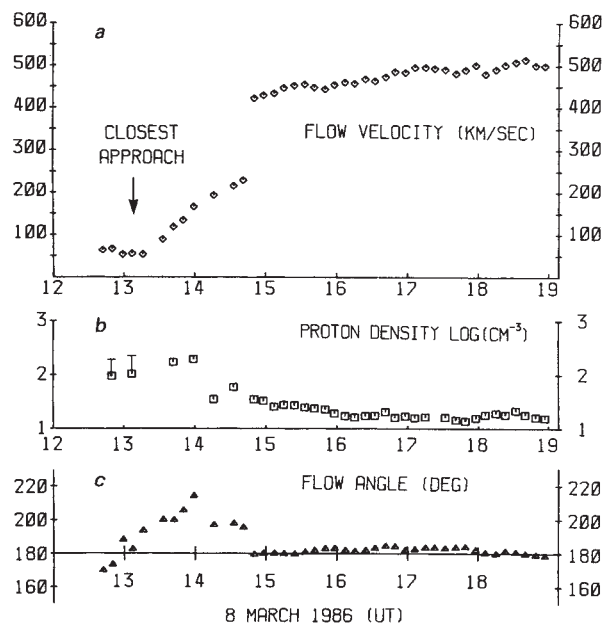


Fig. 2 Bulk flow velocity (a), proton density (b), and flow direction (c) of the solar wind. The flow vectors and angles are represented in the rest frame of the comet.

error of $\sim 15\%$.)

Plasma flow. Figures 1 and 2 show the result of plasma-flow observation during Suisui's encounter with comet Halley. In Fig. 1 the observed flow pattern is shown by arrows starting from Suisui's position at each epoch. Figure 2 shows variations of flow velocity, proton density and flow direction. (In these figures, the flow velocities and angles are drawn in the rest frame of the comet.) The measured proton density includes contributions from the protons of the solar wind as well as of cometary origin. The ESP detector was switched on at 12:32 UT. From this time till 14:43 UT, Suisui was in the ionosphere of the comet, which is evidenced by a characteristic pattern of the flow around an obstacle. The minimum flow velocity, $54 \pm 10 \text{ km s}^{-1}$, was observed around 13:16 UT, when Suisui was in the subsolar direction from the cometary nucleus. The flow pattern inside the cometary ionosphere is roughly symmetric with respect to the direction 4 – 6° from the solar direction. (Since the velocity of the comet with respect to the Sun was $(-24, 37, -12) \text{ km s}^{-1}$, the flow direction of the solar wind with velocity of 400–500 km s^{-1} is expected to incline by 4 – 6° from the solar direction in the comet frame.) Inside the ionosphere, the proton density can be determined only for the samples obtained in scan mode L because of the slow flow speed, while the flow velocities and angles can be determined for all samples. The estimation of

proton density around the closest approach suffers a large error (a factor of ~ 2) because of the slow flow speed.

During the observation gap between 14:43 and 14:49 UT when Suisei was around 4.5×10^5 km away from the nucleus, the plasma parameters changed remarkably. The flow velocity increased from 240 km s^{-1} to 440 km s^{-1} , and the flow direction changed by $\sim 16^\circ$. This change in the flow is interpreted to be due to an outbound crossing of the cometary bow wave (or shock). The upper limit of the bow-wave thickness set by this observation is 2.6×10^4 km. A possible shape of the cometary bow wave is drawn by a parabola in Fig. 1, where the nose of the bow wave is assumed to be at 3.5×10^5 km in the direction of the symmetry axis. Beyond the bow-wave crossing, the solar wind continued to change gradually. The velocity and proton density, $440 \pm 10 \text{ km s}^{-1}$ and $35 \pm 5 \text{ cm}^{-3}$ just after the bow-wave crossing, were $510 \pm 10 \text{ km s}^{-1}$ and $15 \pm 3 \text{ cm}^{-3}$ around 17:10 UT, when the spacecraft was 1×10^6 km away from the nucleus. This change is probably due to the mass-loading effect within the upstream solar wind. This conclusion is further supported by the fact that until $\sim 17:00$ UT we could identify a specific feature in the phase space distribution of ions (a velocity space torus) expected from the assimilation process of the cometary ions.

A quantitative problem, however, arises if we calculate the momentum flux carried by the solar wind. The lower limit of the ratio between the momentum fluxes near and far from the comet is calculated as $(35 \times 440^2)/(15 \times 510^2) = 150\%$. This ratio gives the lower limit, since we do not consider the change of mass density due to the addition of heavier cometary ions to the solar wind. Thus the momentum flux near the comet is at least 50% larger than that far away from the comet. Note that the mass-loading process within the upstream solar wind is expected to conserve the momentum flux approximately. (This is because the momentum changing terms, namely the pressure term and the Lorentz force, in the equation of plasma motion are not effective within the supersonic and super-alfvénic solar wind. These terms can become effective only inside the ionosheath where the flow becomes subsonic and sub-alfvénic.) Therefore, the above difference in the momentum flux is probably due to an intrinsic change of solar-wind properties. Further study is necessary to resolve this momentum flux problem.

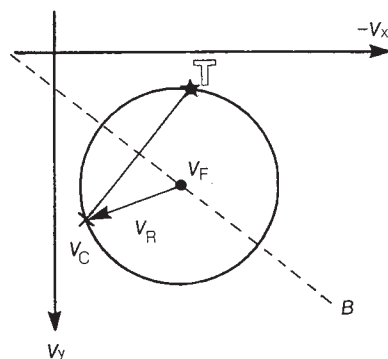


Fig. 3 A schematic illustration of the theoretical model of the assimilation process for the cometary plasma.

Further study is also necessary to understand the nature of the bow wave (or shock). Whereas the clear change in plasma flow characteristics observed at the bow-wave crossing is similar to what was observed at comet Giacobini-Zinner by the ion instrument⁷, it contrasts with the electron observation of the same comet⁸.

Ion pick-up. Figure 3 illustrates the structure in ion velocity space expected for the cometary ion pick-up process (the rest frame of the spacecraft is used here). Since the outflow velocity of the neutral gas from the cometary nucleus (at most several km s^{-1}) can be neglected in the present analysis, newly produced cometary ions are expected to have a velocity V_{HC} , the relative velocity of the comet to the spacecraft (see above). From this velocity, these cometary ions start to rotate around the magnetic field forming a torus in velocity space. V_c is the projection of this initial velocity onto the ecliptic plane, which is $(-18, 70) \text{ km s}^{-1}$ for the present case. When the magnetic field line projected to the ecliptic plane is along a dashed line B within the ecliptic plane, the other side of the torus is to be found at the point shown by a star symbol marked with a T. The pitch-angle scattering process will result in the formation of a shell structure in the velocity space (hereafter referred to as the 'ion-pick-up' shell), whose intersection with the ecliptic plane

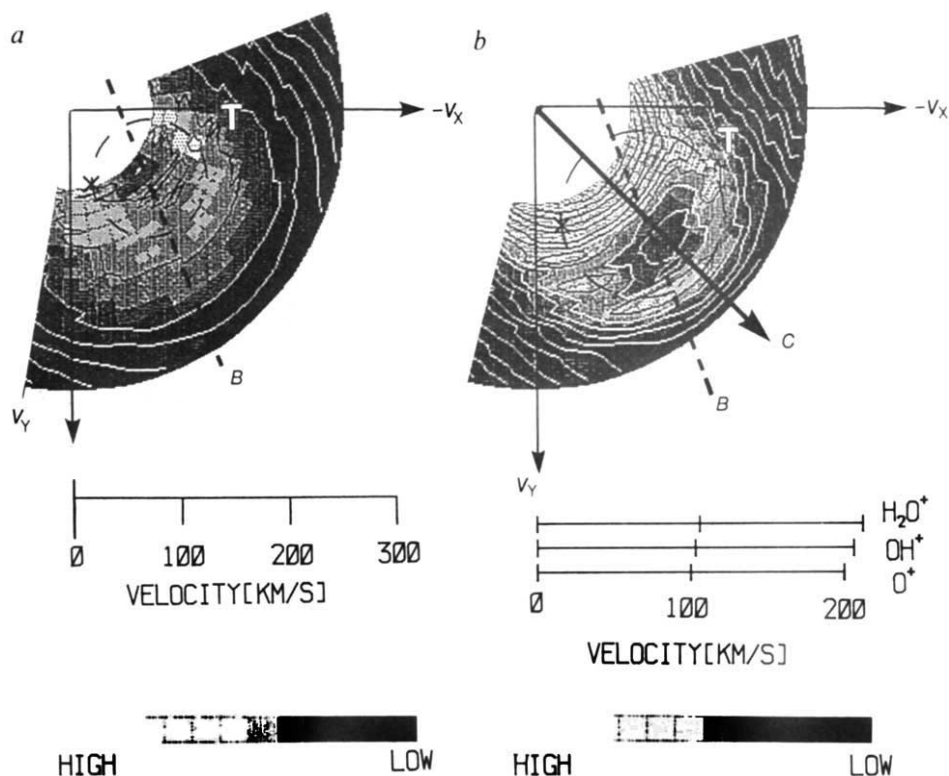


Fig. 4 Velocity-space distributions of: *a*, protons observed during the period 13:06:17-13:08:44 UT; and *b*, water-group ions observed during the period 12:57:45-13:00:12 UT. The grey scales correspond to the ranges (from brightest to darkest): $10^{-7.6}$ - $10^{-8.3} \text{ m}^{-6} \text{ s}^3$ (*a*) and $10^{-6.8}$ - $10^{-8.3} \text{ m}^{-6} \text{ s}^3$ (*b*). A cross-section through the water-group ion distribution (*b*) along the line C is shown in Fig. 5.

is shown by a circle. The radius, V_R , of the shell in velocity space is given by the difference $|V_c - V_F|$, where V_F is the bulk flow velocity. While the torus geometry depends on the magnetic field direction, the shell geometry does not. He^+ ions of interstellar origin picked up through this type of process in the solar wind were discovered by Möbius *et al.*⁹

Figure 4a shows the contour plot of the proton distribution function (30 eV–0.33 keV) observed near closest approach. Contours are drawn at logarithmic steps with an interval 0.2 (for example, $10^{-8.0}$, $10^{-8.2}$, $10^{-8.4}$, ... $\text{m}^{-6} \text{s}^3$). The contours of levels above or equal to (below) 10^{-8} are represented by dark (white) curves. In this figure, grey scales are also used to make the structure of the distribution easier to see. This grey scale is such that the brighter regions correspond to higher phase-space densities. A ring-like structure is seen in Fig. 4a. We interpret this as an intersection of the ion-pick-up shell with the $V_x - V_y$ plane. A small hump, marked T, is likely to be a remnant of the torus of the assimilation process. From the position of T and the expected initial velocity V_c (cross), we can estimate the direction of the magnetic field (**B**). By fitting a circle to the ring-like distribution, we can obtain the following estimates of the flow velocity and the shell radius: $V_F = (-74 \pm 10, 68 \pm 10) \text{ km s}^{-1}$ and $V_R = 56 \pm 10 \text{ km s}^{-1}$.

Figure 4b shows the contour plot of the distribution function in the range 0.2–2.55 keV/ q which was obtained in the interval before the previous sample (Fig. 4a). Again a ring-like structure is seen, which can be most consistently interpreted if we assume that this represents the projected ion-pick-up shell for water-group ions (O^+ , OH^+ and H_2O^+). The velocity scales of Fig. 4b are for O^+ , OH^+ and H_2O^+ from the top. Contours are represented by dark (white) curves above or equal to (below) $10^{-7.6} \text{ m}^{-6} \text{s}^3$ in logarithmic steps with an interval of 0.2. The levels for contours as well as those for the grey scales are calculated for H_2O^+ ions. For the other ion species, they should be re-scaled by multiplying by a factor $[(M/q)/18]^2$, where M and q are the mass and charge numbers of ions, respectively. A cross shows the position of the initial velocity of the cometary ions, V_c , for the case of H_2O^+ ions. As in the previous case of protons, we see a small hump (indicated by a star symbol marked T), which is likely to be the remnant of the torus structure. (The other side of the torus in the $V_x - V_y$ plane, expected around V_c , cannot be identified because of the masking proton flux below $\sim 1 \text{ keV}$.) The result of the fitting process is shown in Fig. 4b: $V_F = (-72 \pm 10, 62 \pm 10) \text{ km s}^{-1}$ and $V_R = 55 \pm 10 \text{ km s}^{-1}$. A dashed line marked B shows the estimated direction of the magnetic field.

To determine the number density of the cometary ions, N_c , we need to extrapolate the observed ion distribution by taking into account the geometrical relation between the shell and the field of view, since the field of view of the ESP instrument did not cover the whole area of the ion-pick-up shell. We calculate N_c as

$$N_c = N_{\text{OBS}} \frac{V_{\text{shell}}}{V_{\text{OBS}}} \quad (1)$$

where V_{shell} is the total volume of the ion-pick-up shell in the velocity space, and N_{OBS} the number density of ions distributed inside the subvolume of the shell (V_{OBS}) which is within the instrument coverage. The shell thickness needed for the calculation of V_{shell} and V_{OBS} is taken to be 10 km s^{-1} , which is defined as the average thickness of the ring-like region where the phase-space density is above 10% of the maximum value inside the ring. The estimated density of cometary water-group ions is $\sim 10 \text{ cm}^{-3}$ around the closest approach (inside $1.8 \times 10^5 \text{ km}$ from the nucleus; this estimate is preliminary and may include an error of a factor of ~ 2). The density of water-group ions can be estimated up to $\sim 2.3 \times 10^5 \text{ km}$ from the nucleus, where the shell structure can be identified. We observe a decrease of $\sim 50\%$ in the density of water-group ions between 1.8×10^5 and $2.3 \times 10^5 \text{ km}$ from the nucleus.

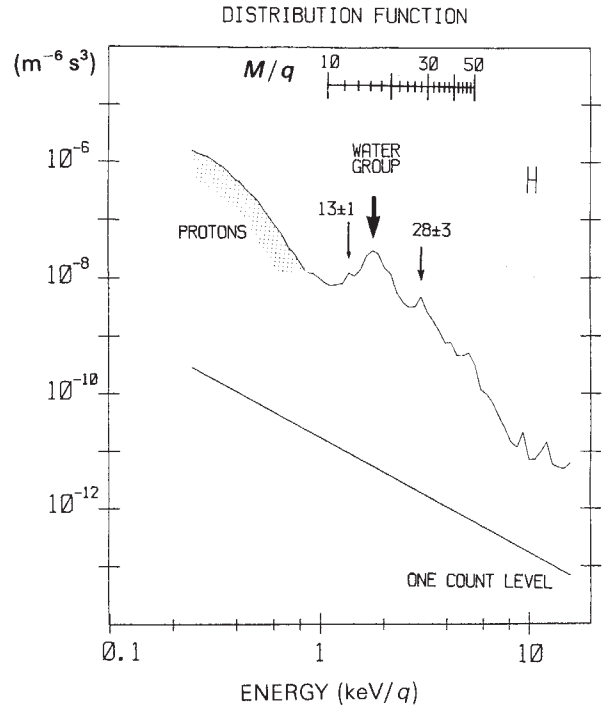


Fig. 5 A section of the distribution function along the line C of Fig. 4b. The scale for M/q is shown at the top, where the peak of water-group ions is adjusted to $M/q = 16$ –18. A small bar shows a possible error in the identification of M/q corresponding to a 10% fluctuation in the flow velocity.

Figure 5 shows a cross-sectional plot of the distribution function along the line C in Fig. 4b, which is taken in the direction of the flow velocity, V_F . In Fig. 5, the abscissa is in units of energy/charge, and the ordinate is scaled as if all the ions are H_2O^+ . For different ion species, the ordinate should be re-scaled by multiplying by a factor $[(M/q)/18]^2$. Ions around $1.7 \text{ keV}/q$ have been identified as water-group ions in Fig. 4b. Ions below $1 \text{ keV}/q$ are the thermal-tail protons. Pick-up shells of other ions (of mass-to-charge ratio M/q) are to be found at the energy/charge of $(1/2)m_p[V_F + V_R]^2 \times [M/q]$ (m_p is the proton mass). A scale for M/q is drawn at the top of Fig. 5, where the peak of water-group ions is adjusted to $M/q = 16$ –18. Since an interval of 147 s is needed to complete one energy scan, velocity fluctuations during this interval may cause misidentifications of ion species. A small bar in Fig. 5 shows a possible error in M/q determination corresponding to 10% fluctuation of the flow velocity. The peak at $M/q = 28 \pm 3$, whose likely candidates are CO^+ and N_2^+ , is statistically significant. Other less significant peaks are also seen, among them a peak around 13 ± 1 which may represent a contribution of C^+ or CH^+ .

Discussion. It is notable that the ion-pick-up shells, as well as the remnants of the torus of newly picked-up ions expected from simple theory, were clearly identified. From the well-defined shell structure, we could identify several species of cometary ions. The existence of the shell itself gives us important information about the physical process governing the cometary ion assimilation process. The shell structure would be smeared out during transport of the solar wind owing to the fluctuation of the flow speed. In addition, the instability caused by the positive slope in $\partial f / \partial v$ would promote the velocity diffusion toward lower velocities to fill the valley. Therefore, for the ion-pick-up shell to be observable, the production of cometary ions at the measurement should be large enough to overcome these smearing effects.

Next we interpret the observed density of water-group ions in terms of a simple pick-up model^{10,12}. We assume that the

parent neutral molecules escape isotropically with a constant radial velocity $V_n \sim 1 \text{ km s}^{-1}$ from the cometary nucleus. Then the ion production rate (ions $\text{cm}^3 \text{s}^{-1}$) can be expressed as

$$P = \frac{Q\lambda_{\text{ion}}}{4\pi R^2 V_n} \exp(-\lambda_{\text{loss}} R/V_n) \quad (2)$$

where Q is the production rate of water molecules from the nucleus, R is the distance from the nucleus, and λ_{ion} and λ_{loss} are the rates of ionization and loss of the parent molecules, respectively. We assume $Q = 1 \times 10^{30} \text{ s}^{-1}$ for water molecules (M. Shimizu, personal communication). During radial expansion, the neutral water molecules are lost by dissociation into $\text{H} + \text{OH}$ and ionization including dissociative ionization. Although the rate of dissociation is much higher than that of ionization, we need not take into account the loss due to dissociation, since our observed density is the sum of densities of water-group ions, $M/q = 16\text{--}18$. Hence, we consider that the loss rate of the parent water molecules is mainly due to ionization and set λ_{loss} equal to λ_{ion} . Among various ionization mechanisms, we consider two main processes: photoionization due to solar extreme-ultraviolet photons and charge exchange with solar-wind ions. We adopt $\lambda_{\text{ph}} = 5 \times 10^{-7} \text{ s}^{-1}$ (converted from the value $3.3 \times 10^{-7} \text{ s}^{-1}$ at 1 AU)¹¹ for photoionization at 0.82 AU, where Suisei encountered the comet. The rate of charge exchange λ_{ex} may be estimated as $\lambda_{\text{ex}} = n_p V_F \sigma = 2.8 \times 10^{-6} \text{ s}^{-1}$, where n_p ($\sim 200 \text{ cm}^{-3}$) and V_F ($\sim 70 \text{ km s}^{-1}$) are, respectively, the measured proton density and flow velocity around closest approach in the cometocentric solar coordinate system. We set $\sigma = 2 \times 10^{-15} \text{ cm}^2$ which is also adopted by Ipavich *et al.*¹⁰. Thus, we take $\lambda_{\text{loss}} = \lambda_{\text{ion}} = \lambda_{\text{ph}} + \lambda_{\text{ex}} = 3.3 \times 10^{-6} \text{ s}^{-1}$.

The newly created ions are then picked up by solar wind, as shown in Fig. 3, and transported downstream toward the spacecraft location. The number density, N_c , of these ions is given by

$$N_c = \frac{1}{V_F} \int_{R_0}^{R_1} P dR \quad (3)$$

where R_0 corresponds to the observation point, and R_1 to the upstream point as described below. The integral should be taken along the stream-line of the solar wind. Ipavich *et al.*¹⁰ took infinity as the upper limit, R_1 , of the integral to interpret their observation during the ICE encounter with the comet P/Giacobini-Zinner, since they measured picked-up cometary ions as a whole. On the other hand, since we are now concerned only with the ion density in the shell structure we set a finite upper limit for the integration to take into account the smearing effect. To calculate the ion density at $R_0 = 1.5 \times 10^5 \text{ km}$, we take $R_1 = 2\text{--}2.5 \times 10^5 \text{ km}$; the flow speed might not be significantly changed between the two points. Moreover, we neglect the disappearance of picked-up ions due to recombination with electrons, since the transportation time ($\leq 10^3 \text{ s}$) between two points of R_1 and R_0 is much shorter than the recombination time. Then, for the spacecraft location at the time of measurement, the number density of the water-group ions can be evaluated as $4\text{--}6 \text{ cm}^{-3}$, in reasonable agreement with the observation ($\sim 10 \text{ cm}^{-3}$), since uncertainties exist in both model calculation and data analysis.

We thank Professors T. Itoh and M. Oda, and all members of the Planet-A project team for their efforts leading to the success of this project. We are also grateful to Drs O. Ashirara, A. Nishida, M. Shimizu and T. Yamamoto for valuable discussion and comments. We appreciate the assistance of JPL/NASA in acquiring the data presented in this paper.

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Interaction between comet Halley and the interplanetary magnetic field observed by Sakigake

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During 10–12 March 1986, the magnetometer carried by the Japanese spacecraft Sakigake detected clear multiple crossings of the nearly horizontal heliospheric neutral sheet. As there was no apparent disconnection event (DE) in comet Halley's ion tail during 11–14 March, an interplanetary magnetic field (IMF)–comet interaction model with a quasi-parallel neutral sheet is proposed to explain why a DE did not occur. Enhancements of hydromagnetic (HM) waves were observed near the time of closest approach to comet Halley. Neutral particles of cometary origin are proposed to yield, at $\sim 7 \times 10^6 \text{ km}$ upstream of the comet, the ionized O^+ (or H_2O^+) particles which excite the HM waves.

The magnetometer, a triaxial ring-core sensor installed at the tip of Sakigake's 2-m boom, began observation on 19 February. Since then the IMF has been observed continuously, and the observations have been analysed in conjunction with the scanning model¹, the two-hemisphere model² and the GBMR (giant bipolar magnetic region) model³. As expected^{4,5}, the heliosphere was in excursion phase, in which the heliospheric neutral sheet was tilted with respect to the ecliptic plane. In the transition from excursion phase to aligned phase, in accordance with the solar-cycle variation of the heliosphere⁶, there was a gradual decrease in the tilt angle. While we were awaiting the closest approach of Sakigake to comet Halley, by watching for changes in the condition of the heliosphere, the Sakigake/IMF data were used also to study the solar–interplanetary–terrestrial relationships for four typical morphological cases⁷, the characteristics of interplanetary discontinuities⁸, and a dynamic pressure effect on the disconnection event of comet Halley on 31 December 1985¹⁷. Here we focus on the magnetometer data obtained near the closest approach of Sakigake to comet Halley at 04:18 UT on 11 March 1986.

On 10 March 1986 (one day before closest approach), the Sakigake data were telemetered to us for $\sim 1 \text{ h}$, from 02:47 to 03:47 UT; during this interval, the Sakigake IMF data showed a stable and distinct 'toward' polarity (that is, inward polarity of the IMF along the Parker spiral). The next signals from Sakigake were telemetered to us over $\sim 13 \text{ h}$, from 19:40 UT on 10 March to 08:37 UT on 11 March (see Fig. 1, where the total field (F), and its θ and ϕ components are shown separately). When the first signals were received at 19:40 UT, the IMF direction already showed 'away' polarity, suggesting that some sector boundary crossing(s) occurred from 03:47 to 19:40 UT on 10 March. At 20:49 on the same day, the IMF showed a polarity change (probably of a slow reverse shock), followed by characteristic switches of polarity from away to toward, and vice versa, until $\sim 02:00$ on 11 March. After this, the total field remained at a

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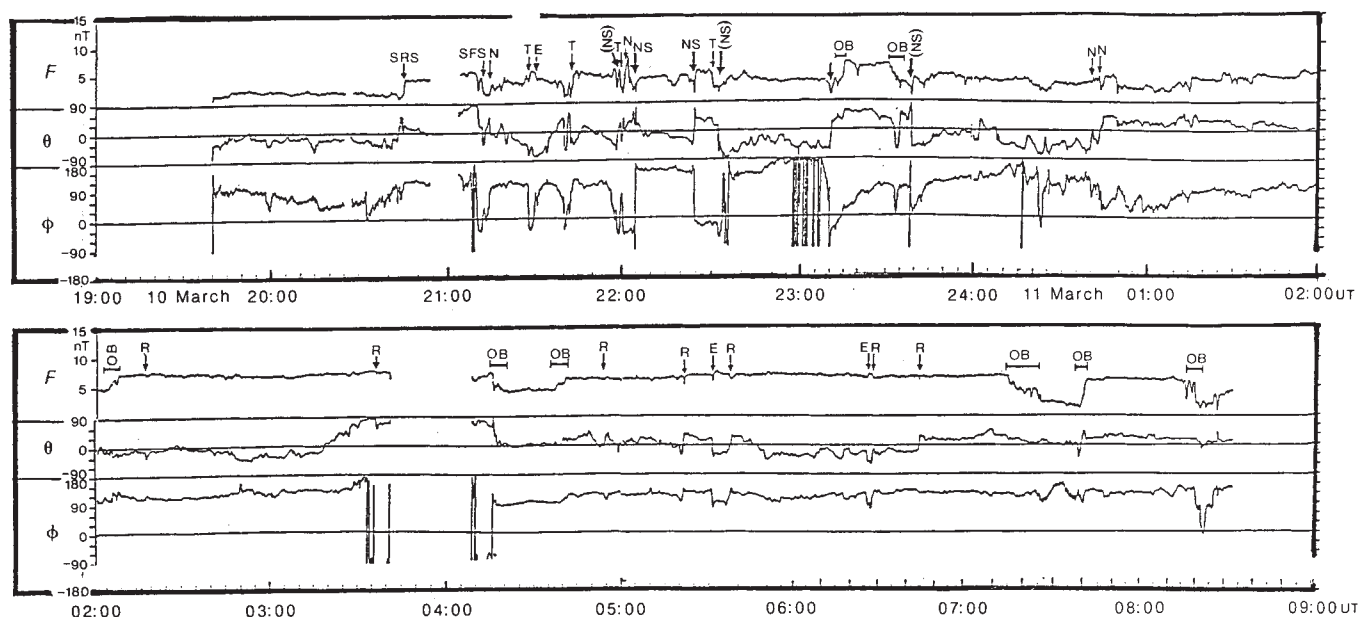
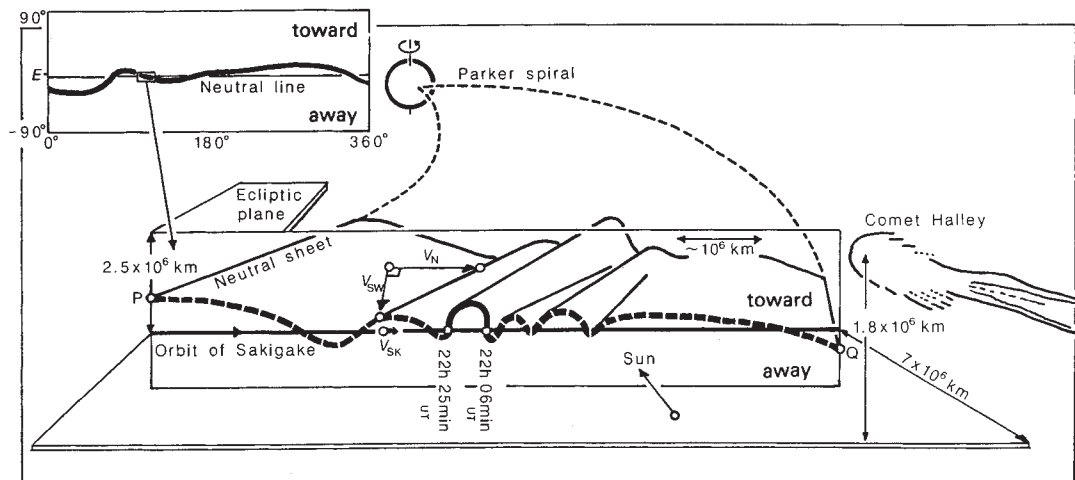


Fig. 1 The total field (F), θ component (inclination) and ϕ component (declination) of the solar-wind magnetic field observed by a triaxial ring-core magnetometer onboard Sakigake from 19:40 UT on 10 March to 08:34 UT on 11 March 1986. The time of closest approach was 04:18 on 11 March. Discontinuities (R, T, E and N), shocks (SFS, SRS, FFS and FRS), the heliospheric neutral sheet (NS), and outer boundary (OB) of the supposed magnetic cloud or a supposed interplanetary plasma sheet are indicated by the arrows. $\phi \approx 135^\circ$ represents the away polarity, while $\phi \approx -45^\circ$ represents the toward polarity.

Fig. 2 Inset: The neutral on the source surface of the Sun, inferred by applying the scanning method to the observed IMF data. We used a comparison of the Stanford solar magnetogram (T. Hoeksema, personal communication) and the interplanetary scintillation data of Kojima and Kakinuma (personal communication) to draw the curve. The lower panel shows a schematic illustration of the relationship between the Sun, the neutral sheet, Sakigake and comet Halley. The crossings of the two tangential discontinuities satisfying the four criteria (see text) are marked by the open circles on the representation of the heliospheric neutral sheet. The other parts of the curve are denoted by thick broken lines, as the tangential discontinuities observed by Sakigake do not satisfy all of the four criteria. The solar-wind speed (v_{sw}), the apparent speed (v_N) of the cross-section of the neutral sheet along the vertical plane including the Sakigake orbit, and the orbital speed of Sakigake (v_{sk}) are noted.



fairly stable level of ~ 8 nT with away polarity until 08:32, except for three intervals (04:10–04:41, 07:13–07:40 and 08:15–08:32) during which F decreased to 2–5 nT. Judging from the telemetry signals received in the 8-h interval after 19:37 on 11 March, the IMF showed away polarity with some fluctuations, which decreased gradually until 03:47 on 12 March.

The heliospheric condition inferred from the Sakigake data was confirmed by other solar, interplanetary and terrestrial observations, including the observations of the Stanford solar magnetogram (T. Hoeksema, personal communication) and interplanetary scintillation data (Y. Kojima and K. Kakinuma, personal communication). Figure 2 (inset) shows the neutral line, inferred from these data, on the solar source surface. If the neutral line is extended radially and forms the heliospheric neutral sheet, it is considered that between 10 and 11 March

Sakigake crossed the neutral sheet (corresponding to the part enclosed by a rectangle in Fig. 2). The IMF disturbances on these days were analysed and classified into the following four categories: (1) The first category represents a group of interplanetary discontinuities including rotational (R), tangential (T), either of these (E), and neither (N)⁸. (2) The second category comprises the shock group, which is further classified into slow forward shock (SFS), slow reverse shock (SRS), fast forward shock (FFS), and fast reverse shock (FRS). (3) The third category consists of the heliomagnetospheric neutral sheet (NS) or the current sheet. A tangential discontinuity is regarded as the neutral sheet when it satisfies the following four conditions: (i) switching of the sector polarity occurs within $180 \pm 30^\circ$ with respect to the Parker spiral, (ii) the switching of the sector angle, ϕ , corresponds to the switching of the polarity of the θ com-

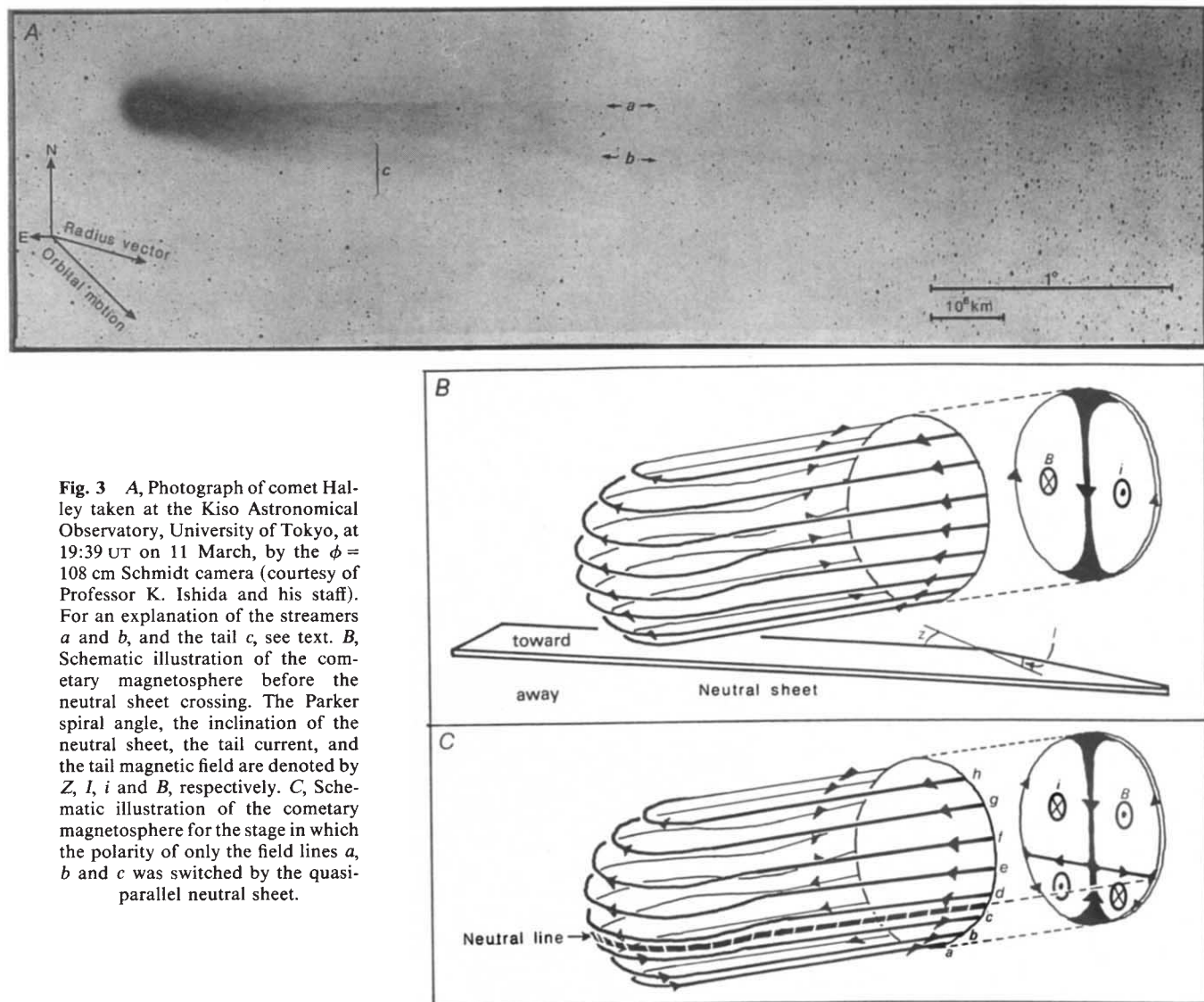


Fig. 3 A, Photograph of comet Halley taken at the Kiso Astronomical Observatory, University of Tokyo, at 19:39 UT on 11 March, by the $\phi = 108$ cm Schmidt camera (courtesy of Professor K. Ishida and his staff). For an explanation of the streamers *a* and *b*, and the tail *c*, see text. B, Schematic illustration of the cometary magnetosphere before the neutral sheet crossing. The Parker spiral angle, the inclination of the neutral sheet, the tail current, and the tail magnetic field are denoted by Z , I , i and B , respectively. C, Schematic illustration of the cometary magnetosphere for the stage in which the polarity of only the field lines *a*, *b* and *c* was switched by the quasi-parallel neutral sheet.

ponent, (iii) the total field is at a minimum at the moment of switching, and (iv) the interval between two successive discontinuities must be longer than 10 min⁸. Neutral sheets satisfying all four of these criteria occur at 22:06 and 22:25 UT. (4) The fourth category comprises the peculiar changes in the total field from 2–5 nT to a constant ~ 8 nT, or vice versa. These changes can be considered to be crossings of Sakigake from the solar plasma sheet, through its outer boundary (OB), into a supposed magnetic cloud or a supposed interplanetary lobe, or vice versa.

All these groups and subgroups are indicated in Fig. 1 (arrows).

Figure 2 also shows the positions of Sakigake, the Sun, the supposed neutral sheet, and comet Halley. The neutral sheet aligned along the Parker spiral is conveyed radially by the solar wind with a velocity v_{sw} . If we take the cross-section of the sheet to be a vertical plane incorporating the Sakigake orbit, the cross-section apparently moves rightwards in the plane with $v_N = v_{sw} \tan \chi$, where χ is the angle between the plane and the Parker spiral, and v_N is the apparent velocity component of the neutral sheet along the Sakigake orbit. As the orbital velocity of Sakigake, v_{sk} (~ 70 km s⁻¹), is rightwards and is much less than v_N (~ 450 km s⁻¹), the spacecraft crosses the neutral sheet from right to left.

It is certain that Sakigake crossed the neutral sheet at least four times: once (or more) in the interval from 03:47 to 19:40

on 10 March, at 22:06 and 22:25 on the same day, and once (or more) from 22:25 on 10 March to 19:36 on 12 March. Although the calculated inclinations of the tangential discontinuities are taken into consideration in Fig. 2, only those crossings of the neutral sheet that satisfy the four conditions are shown (two open circles linked by a thick solid curve). The average inclination of the neutral sheet may be estimated from points P and Q in Fig. 2. We conclude that Sakigake made multiple crossings of the nearly horizontal neutral sheet.

Niedner and Brandt⁹ proposed that an old ion tail of a comet is replaced, by means of a disconnection event (DE), with a newly grown ion tail every time the comet penetrates a (perpendicular) sector boundary. We now apply their model to our case of the sector boundary crossings between 10 and 11 March 1986. We were fortunate in obtaining precise information concerning the sector boundary located 7×10^6 km upstream of comet Halley on the day of closest approach. If we take 450 km s⁻¹ as the solar wind speed and 0.3 AU (ref. 10) for the length of Halley's ion tail, it takes longer than 1 day (28 h) for the solar wind to pass through the entire ion tail. Hence, if a DE occurs and passes through the entire ion tail, it will be observable from any point on the Earth. However, our tentative conclusion is that no distinct DE can be seen in Halley's ion tail during 11–14 March, in the data from Asia, Australia and the United States.

As an example, Fig. 3A shows a photograph of comet Halley

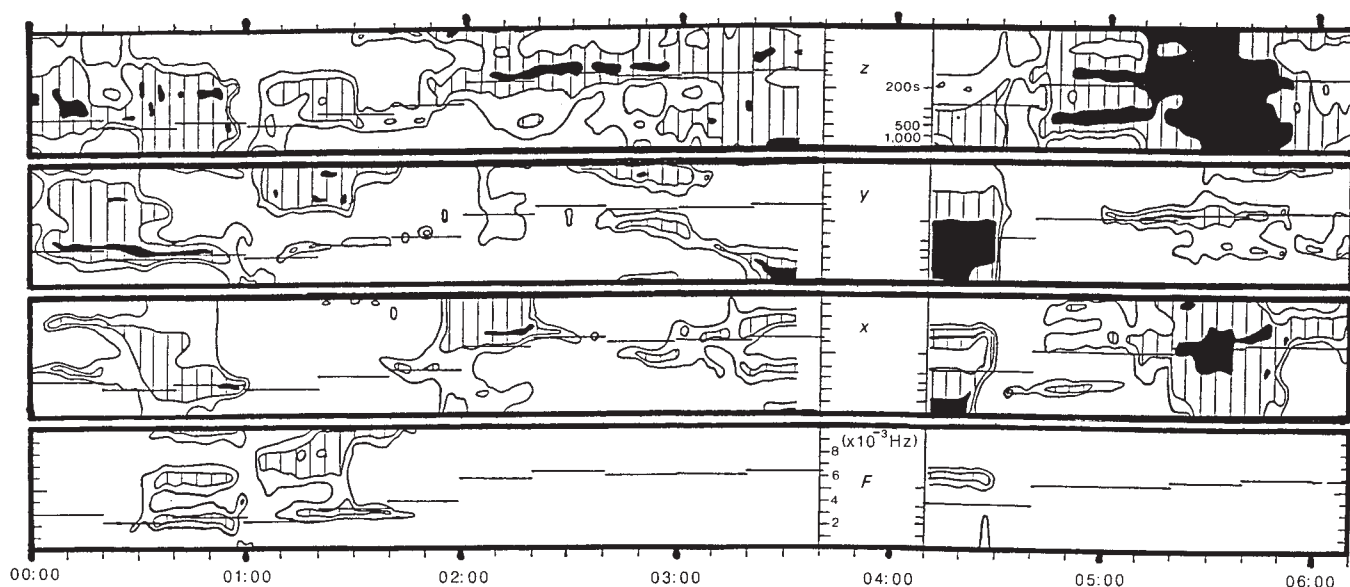


Fig. 4 Dynamic spectrograms for the z , y , x and F components of IMF for the period 00:00 to ~06:10 on 11 March 1986. The thin horizontal lines indicate the cyclotron frequency for O^+ (or H_2O^+). The coincidence of the lines and the enhancement of the waves in y for ~00:00–02:00 UT and in z for 01:00–03:30 suggests the possible existence of cometary ions near Sakigake.

taken at the Kiso Astronomical Observatory, University of Tokyo, on 11 March at 19:39 UT by the largest ($\phi = 108$ cm) Schmidt Camera in Asia. (Pictures taken by Mr Nishitani in Sydney at 19:11 UT and by Mr Kawazoe in Kohchi at 19:52 UT (and at other times) on the same day show a similar feature.) There are two distinct streamers (indicated by a and b in Fig. 3A). The helical structure which is clearly seen in the two streamers near the coma is noteworthy in relation to the wavy structure of the neutral sheet (see Fig. 2).

As a distinct DE did not occur in Halley's ion tail, we propose the model shown in Fig. 3B, C for the approach of a quasi-parallel neutral sheet to the comet. Before the neutral sheet was crossed, comet Halley was in the 'toward' hemisphere. Hence, the magnetic field lines of the cometary magnetosphere must be horizontal on average, with a vertical, downward-pointing current sheet (i), as shown schematically in Fig. 3B. In almost all previous models of the cometary magnetosphere, the vertical (z component) interplanetary magnetic field lines are draped by the cometary nucleus. However, the averaged three-dimensional view must rather comprise horizontal field lines with the vertical tail current sheet, as was almost the case for comet Giacobini-Zinner¹⁸.

In our case, a neutral sheet with a small angle of inclination, I , and with Parker spiral angle χ , was conveyed by the low-speed solar wind as illustrated in Fig. 3B. As $\chi \sim 45^\circ$, the attack angle of the neutral sheet could be as small as the angle I , although the angle could be slightly increased by mass loading upstream of comet Halley. Hence, the southern part of Halley could be dipped first into the away sector, changing the polarity of the field line 'a' from toward to away polarity by means of Niedner's reconnection process. Associated with the dipping of comet Halley into the apparently upwelling neutral sheet, the polarity of the field lines b , c , d , ... h could be switched one after the other. Figure 3C indicates an intermediate stage, in which only the field lines a , b and c have switched to away polarity; this situation gives rise to a neutral line (thick broken line) and a horizontal tail current. The change of the whole field-line polarity from toward to away could be accomplished by a shift of the neutral line and the horizontal tail current from the southern edge to the northern edge. When the Niedner-type reconnection is gradually executed from a to h (Fig. 3C), a drastic DE cannot be observed. It must be noted in relation to this model that a

peculiar tail 'c' with many fine rays was visible only on 11 March on the southern side of the tail b in Fig. 3A.

In order to detect ions of cometary origin, a dynamic spectrogram was constructed from the observed IMF data for the total field (F), and its x , y and z components in solar ecliptic coordinates, as presented in Fig. 4 (which shows only the 6-h interval including the time of closest approach). The horizontal solid lines in Fig. 4 represent the local O^+ (or H_2O^+) cyclotron frequency, which was estimated using a 20-min average of the total field. Enhancements of linearly polarized oscillations can be seen in the y component, with a period of ~375 s, from ~00:00 to ~02:00 UT, and in the z component, with a period of ~150 s, from ~01:00 to ~03:20 UT. The change of the predominant component from y to z was correlated with a change in the direction of the ambient magnetic field, from z to y , near 01:30 UT. The frequencies of the enhanced oscillations coincide with the local O^+ (or H_2O^+) cyclotron frequencies.

The results of a preliminary analysis of the long-period waves can be summarized as follows: (1) The wave amplitudes are as large as ~2 nT peak-to-peak. The ratio of the perturbation field to the averaged field strength ranges from 0.2 to 0.5. (2) The period of the waves is in the range 150–375 s, which is consistent with the local O^+ (or H_2O^+) cyclotron period. (3) The waves are linearly polarized and in transverse mode.

Wu and Davidson¹¹ demonstrated theoretically that even if the density of newly ionized particles (n_{in}) is only a very small fraction of that of the solar wind, these particles can efficiently excite HM waves by means of a resonant instability. When n_{in} is very small, the instability condition requires a very large characteristic speed ($v_{||}$) of the newly ionized ions parallel to the ambient magnetic field in the frame of the solar wind. Recently, Tsurutani and Smith^{12,13} found that the intense HM turbulences surrounding comet Giacobini-Zinner extended to cometocentric distances beyond 10^6 km. They investigated the possibility that the long-period waves were generated by resonant instability¹¹ with the pick-up of freshly ionized cometary neutrals. Although further studies of the wave characteristics of the long-period HM waves having the local O^+ (or H_2O^+) cyclotron frequency and of the pick-up of newly ionized O^+ (or H_2O^+) group ions are needed, the long-period HM waves observed 7×10^6 km upstream of comet Halley are believed to be excited by O^+ (or H_2O^+) ions originating from the comet.

From the limited information and photographs obtained from comet watchers in Asia, the United States and Australia, a distinct DE has not been found so far. As ours represents the first experiment to observe the neutral sheet in the upstream region of a comet, any photographs of comet Halley taken between 11 and 14 March would be valuable. (Any such photographs, or other information on a possible DE of comet Halley during 11–14 March 1986, should be sent to T.S.).

Sakigake observed the crossing of the next sector boundary during 18–19 March 1986. In contrast to the quasi-parallel boundary crossing of 10–12 March, the 18–19 March boundary crossing was rather perpendicular. Hence, it would be worthwhile making a comparative study of the neutral sheet–comet Halley interaction for the quasi-parallel case and the perpendicular case.

The heliospheric neutral sheet configuration on a given day in the past can be estimated from geomagnetic activity indices by applying the two-hemisphere model to the solar-cycle variation of the three-dimensional heliosphere, even for days on which direct solar-wind data from spacecraft are not available. We were able to study the interaction between the neutral sheet and comet Halley for the 13 May 1910 event¹⁴; thus, it may be worthwhile studying old photographs of comets, including the famous DE of comet Morehouse during September–October 1908, in relation to the inferred heliospheric neutral sheet.

We have raised the possibility of an effect of the O^+ (or H_2O^+) ions of comet Halley at 7×10^6 km ahead of the comet, based on the dynamic spectrograms of the Sakigake IMF data. Our result shows good agreement with the Sakigake plasma-wave¹⁵ and solar-wind¹⁶ experiments. These results suggest that the effects of comet Halley can be detected over a wider area than was previously expected.

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Discovery of cometary kilometric radiations and plasma waves at comet Halley

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The plasma-wave probe carried by the spacecraft Sakigake discovered discrete spectra of emissions from comet Halley in the frequency range 30–195 kHz. The observed cometary kilometric radiation appears to come from moving shocks in the coma region which are possibly associated with temporal variations of the solar wind. Waves due to plasma instabilities associated with the pick-up of cometary ions by the solar wind were observed within a region almost 10^7 km from the comet nucleus.

The plasma-wave probe (PWP) system carried by the Sakigake spacecraft used two detectors: a 10-m tip-to-tip dipole antenna and a search coil-type magnetic field detector. The receivers of the PWP system comprised a swept frequency receiver and a 16-channel frequency analyser, referred to as the extremely-low-frequency (ELF) receiver, which has a constant bandwidth of 100 Hz.

The swept frequency analyser for the low-frequency (LF) range analysed the signal in 125 frequency steps from 4 to 195 kHz with a bandwidth of 1 kHz in all frequency ranges. Due to the limited length of the dipole antenna, the threshold for the detection of the electric field was changed so as to be inversely proportional to the observation frequency; that is, $1.3 \mu V m^{-1}$ for 195 kHz, $2.6 \mu V m^{-1}$ for 100 kHz and $26 \mu V m^{-1}$ for 10 kHz. For our measurements of the electric field components for the LF and ELF receivers, we mainly used the 10-m tip-to-tip antenna. The threshold level in the ELF range was $0.26 mV m^{-1}$ for 1 kHz and $0.52 mV m^{-1}$ for 500 Hz; that is, we were able to observe propagating electromagnetic waves in the LF range, but were able to measure only *in situ* electrostatic plasma waves in the ELF range (see Fig. 4 for observation frequencies) at the time of closest approach to the comet. The data transmission rate was minimal, 64 bits s^{-1} , at the time of closest approach, because the spacecraft was $>10^8$ km from

Trajectory of Sakigake

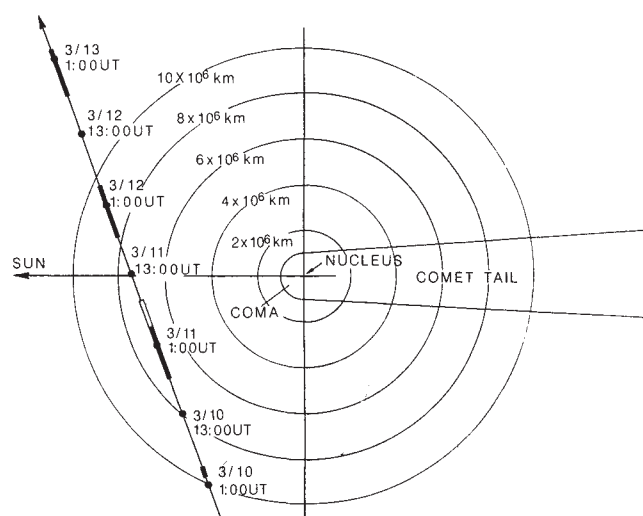


Fig. 1 The trajectory of the Sakigake spacecraft during the period of closest approach to comet Halley. The observations were made during each period shown by a thick line; an open segment shows the period of the data recording mode operation.

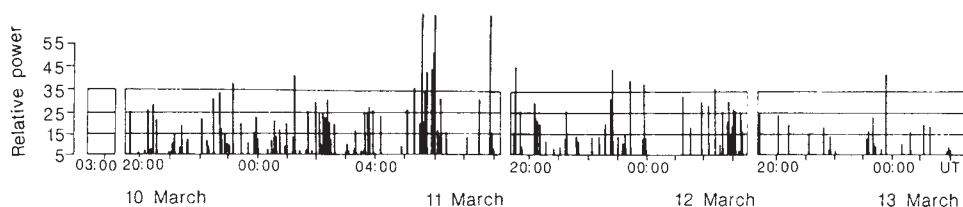


Fig. 2 Variation of the power of the LF emissions from comet Halley during the encounter, integrated over a frequency range of 4–195 kHz.

Earth; we therefore used the temporal memory to store the spectra. The stored spectra were transmitted every 125 s.

Observations during the period of closest approach. Figure 1 shows the path of Sakigake during the time of closest approach, together with the observation periods. The spacecraft passed through the upstream region of the comet, where the solar wind with average velocity 400 km s^{-1} will take 4 h to travel from the spacecraft to the cometary coma. Figure 2 shows the intensities of the plasma waves integrated over the frequency range 4–195 kHz. It is apparent that the intensity of the emissions increases, with the maximum intensity occurring during closest approach, thus indicating that the emissions are intimately related to the comet.

Figure 3 gives all the observation data for the plasma-wave spectra in the LF range; note that the records are contaminated by interference noise. As indicated in panels D1 and D2, the only discernible emission is that due to interference from onboard instruments for the data obtained on 13 March, when the spacecraft moved away from the comet to a distance of more than $1.2 \times 10^7 \text{ km}$. The signals at each frequency in the dynamic spectrum show the interference of d.c.–d.c. converters, and the harmonics of the exciter signal from the ring core magnetometer where the square wave at 6.5 kHz is applied. On 11 March, the day of the closest approach to the comet, emissions definitely attributable to the comet were observed (Fig. 3, panels A1, B1, A2, B2). The data for the real-time observations from 19:40 to 03:45 UT and from the data recorder for observations made from 03:45 to 07:45 UT are shown respectively in panels A1, B1, A2 and B2 of Fig. 3. The emissions are characterized by discrete spectral features with rising tones, falling tones and a complex

of rising and falling tones (Fig. 3, panels A3, B3). In addition to these discrete-type emissions, there are also broad-band emissions which are enhanced in the cometary plasma. Data showing similar characteristics for the comet emissions were also obtained on 12 March from 19:45 to 03:45 UT (see Fig. 3, panels C1, C2, C3) as the spacecraft was moving from $8 \times 10^6 \text{ km}$ to 10^7 km from the cometary nucleus.

Cometary kilometric radiation. We have designated the emissions in the frequency range from 30 kHz to 195 kHz as cometary kilometric radiation (CKR), and have classified the observed emissions into three types: D, S and C.

(1) Type D emissions. An emission whose frequency increases continuously is called type D_R (rising tone). An example of this type can be seen from 23:30 UT (on 10 March) to 03:00 UT (on 11 March). In most cases, the rising tones of type D_R emission start at around 100 kHz and end at around 160–190 kHz. Examples of type D_R emissions chosen from the observed cometary radio emissions are listed in Table 1(a, type D_R).

In contrast to the monotonic increase in frequency for type D_R emission, we also observed discrete emissions whose frequencies decreased monotonically; we call these type D_F emissions. The emission frequency begins to fall at ~180–190 kHz and decreases to a frequency range of 60–80 kHz. Table 1(b, type D_F) gives examples of type D_F emissions chosen from the observations.

Complex-type emissions, called Type D_C , a combination of types D_R and D_F , were also observed.

(2) Type S emissions. The observed dynamic spectra contain bursts lasting less than a few seconds, which we call sporadic

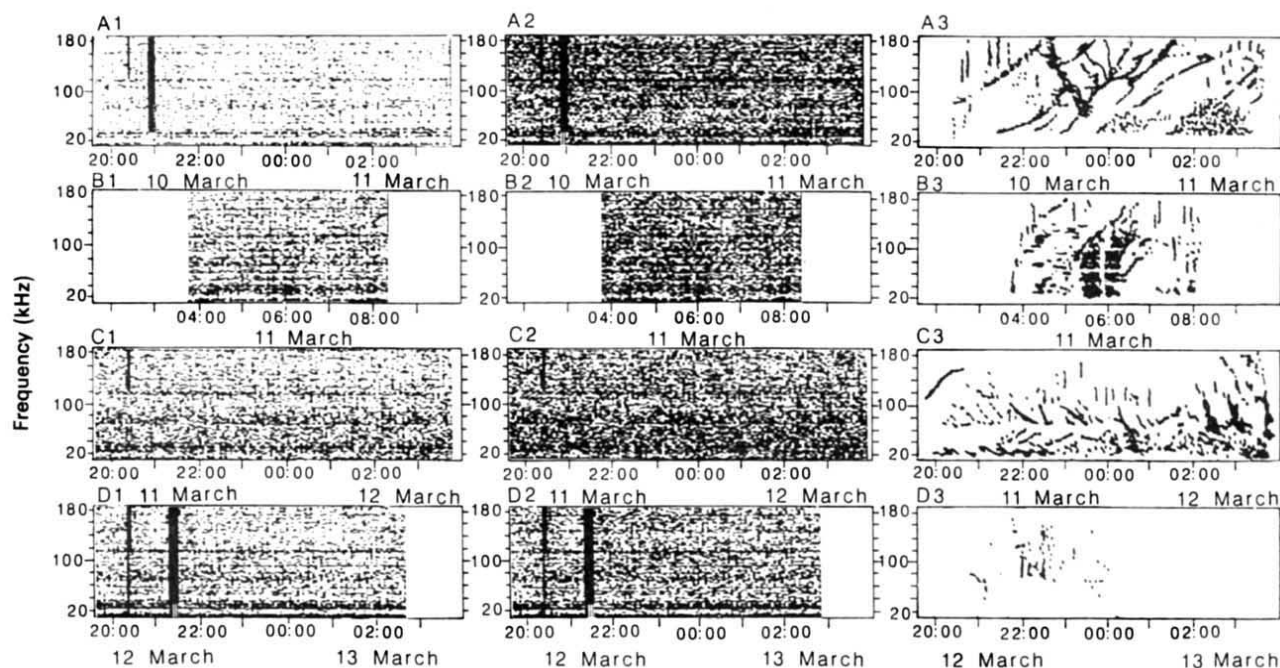
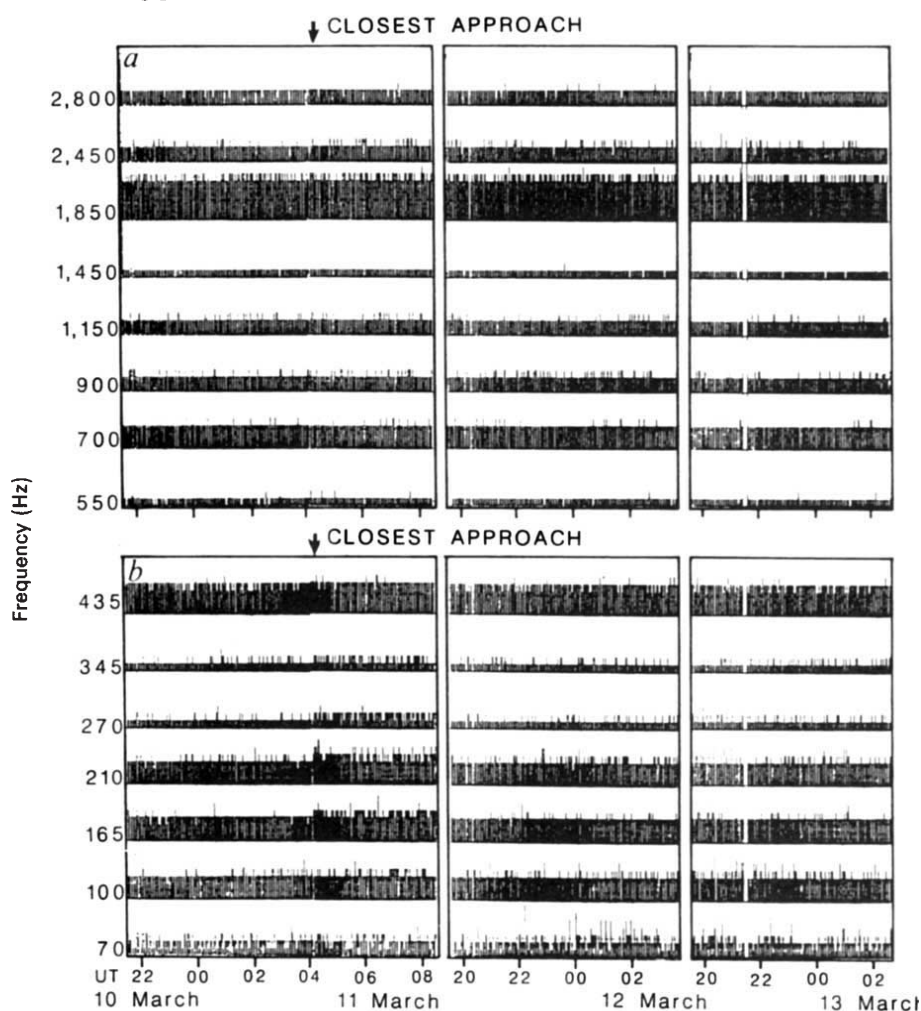


Fig. 3 Dynamic electric field spectra of the observed LF emissions in the frequency range 10–195 kHz in the period of the encounter. Panels A1–D1 show results for the threshold level $1.6 \mu\text{V m}^{-1}$ at 100 kHz and $16 \mu\text{V m}^{-1}$ at 10 kHz. The column containing panels A2–D2 shows the dynamic spectra corresponding to the threshold level $0.53 \mu\text{V m}^{-1}$ at 100 kHz and $5.3 \mu\text{V m}^{-1}$ at 10 kHz. The column containing panels A3–D3 shows emission spectra. The indicated periods of data are therefore the same for each line of panels; for example, A1, A2 and A3.

Fig. 4 Spectra obtained by a 16-channel analyser in ELF ranges of 70–2,800 Hz during the approach to comet Halley. No remarkable enhancement was detected in the frequency range 550–2,800 Hz (in *a*), but very clear increments of emissions were detected in the low-frequency range 70–435 Hz (*b*), particularly during the period of closest approach. The maximum level recorded 20 mV m^{-1} at 210 Hz, and levels of $\sim 15 \text{ mV m}^{-1}$ were frequently seen in the frequency range 70–270 Hz.



or type S emissions. These emissions are also characterized by their intense broad-band nature. The intensity of the type S emissions increased gradually with decreasing distance from the comet, and began to decrease again with increasing distance after closest approach to the comet.

(3) Type C emissions. The broad-band emissions were enhanced as the spacecraft approached the cometary nucleus. The intensity integrated over the total observation-frequency range is shown in Fig. 2. We call these broad-band emissions cometary continuum radiations, or type C emissions.

Table 1 Examples of type D_R (*a*) and D_F (*b*) emissions

Date	Case	Starting time (UT)	Ending time (UT)	Starting frequency (kHz)	Ending frequency (kHz)
<i>a</i> , Type D_R 10–11 March	1	20:30	22:23	80	177
	2	21:30	23:00	33	114
	3	22:39	23:30	140	195
	4	23:00	00:19	40	195
	5	23:56	00:43	120	160
	6	00:19	01:15	120	195
	7	00:19	02:00	80	155
	8	19:48	20:30	110	157
<i>b</i> , Type D_F 11 March	9	22:35	23:17	180	70
	10	23:17	23:56	160	120
	11	23:38	23:56	180	120
	12	21:40	22:16	100	70
	13	22:16	22:32	100	70

***In situ* plasma waves in the ion pick-up regions.** Very intense broad-band emissions, distinct from type C emissions, were observed which were attributed to *in situ* emissions in the ion pick-up region lying within the hydrogen coma through which the spacecraft passed. Figure 3 (panels B1, B2, B3) shows an example of such emissions at around 06:00 UT, the time of closest approach.

In addition to the very intense electrostatic plasma waves due to electron plasma oscillation observed near 06:00 UT on 11 March, ion sound waves were also observed (Fig. 4*b*). The electron plasma waves and ion sound waves were detected with intensities of 0.2 mV m^{-1} (for 10 kHz) and $\sim 15 \text{ mV m}^{-1}$, respectively, for the frequency range 70–270 Hz. The *in situ* emissions may be similar to the plasma waves detected at comet Giacobini-Zinner¹, but the region of the ion pick-up was larger in the case of comet Halley.

Possible origins of CKR. Discrete emissions indicate that the frequency changed from 60 to 195 kHz during periods of 30–40 min. This cannot be interpreted in terms of the frequency dispersion but can be attributed to the movement of the radio sources. It may be assumed that the emissions are occurring at the local plasma frequency. The possibility of conversion of the electrostatic plasma waves due to the turbulence of the plasma has long been considered^{2–4}. Basically, the conversion of the electrostatic plasma waves to electromagnetic waves takes place through the plasma turbulence regardless of whether or not the plasma contains a magnetic field. For the present purposes, we need not consider the nonlinear regime for the conversion process because the turbulence is less intense than in the case of solar type II bursts, where very intense shock waves generate the second-harmonic waves associated with the fundamental

Table 2 Cases of moving shock

Case	Time interval (min)	Starting position (10 ⁶ km)	Ending position (10 ⁶ km)	Average speed of moving shock relative to nucleus (km s ⁻¹)	Comments
1	113	1.00	0.45	81	Inward motions
2	90	2.43	0.70	320	
3	51	0.57	0.41	52	
4	79	2.00	0.41	335	
5	47	0.67	0.50	60	
6	56	0.67	0.41	77	
7	101	1.00	0.52	79	
8	42	0.73	0.51	87	
9	42	0.45	1.15	278	Outward motions
10	39	0.50	0.67	73	
11	18	0.45	0.67	204	
12	36	0.80	1.15	162	
13	16	0.08	1.15	364	

Case numbers correspond to the examples given in Table 1.

plasma frequency emissions. The plasma density distribution in the coma region of comet Halley is estimated for a molecular production rate of 10^{30} s^{-1} ; the estimated values provide the moving source regions of the emissions as given in Table 2.

The monotonically decreasing frequency of type D_R emission therefore indicates the movement of the shock within $2 \times 10^6 \text{ km}$, mostly from 1 to $0.4 \times 10^6 \text{ km}$, with the moving velocity ranging from 60 to 335 km s^{-1} . The movement of the shock towards the upstream region of the solar wind is also revealed by the type D_R emissions. That is, the radio sources associated with the shock waves move from the inside region of the coma at a distance of $0.45\text{--}0.80 \times 10^6 \text{ km}$ towards the upstream region until the shocks arrive at the region $\sim 10^6 \text{ km}$ from the nucleus.

The solar wind, when the Sakigake spacecraft moved across the upstream region of the coma, contained fairly large disturbances because the neutral sheet regions of the heliomagnetosphere passed through comet Halley. Several marked discontinuities of the magnetic field with plasma density variations were observed on 11 March. Particularly on 12 March, the enhancement of the radio emissions was observed to be associated with the encounter of the turbulent regions of the heliomagnetosphere with Sakigake and comet Halley. That is, after passing through the turbulence^{5,6} with a delay time of $3\frac{1}{2} \text{ h}$, the emissions increased markedly. This delay time is a reasonable one for the transport time of the turbulence to the coma region of the comet.

The observed type D_F and D_R emissions are thus inferred to result from moving shock or bow waves in the coma region of the comet due to time-dependent variations in the solar wind.

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Was the solar wind decelerated by comet Halley?

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The velocity, ion density, flow direction and ion temperature of the solar-wind plasma were measured during Sakigake's approach to comet Halley from 10 to 13 March, with a distance of closest approach of $7 \times 10^6 \text{ km}$. Interplanetary magnetic field (IMF) observations show that Sakigake travelled through the solar plasma sheet and also through the lobes of the heliomagnetosphere (or through the magnetic cloud). At the time of the measurements, interplanetary space was undergoing a small disturbance caused by the two-stream solar wind with a 27-day periodicity. Although it is difficult to isolate an effect of the comet on solar-wind parameters from background disturbances, it remains possible that the solar wind was decelerated by the cometary atmosphere.

Japan's first interplanetary space probe Sakigake passed on the sunward side of comet Halley at a distance of $7 \times 10^6 \text{ km}$, at 04:17 UT on 11 March. The solar-wind parameters such as wind velocity, ion density, flow direction and ion temperature were measured by means of a Faraday cup^{1,2}. The data from the Sakigake probe should provide at least an upper limit on the effects of the comet on solar wind, when taken together with data from the other Halley probes.

Instrumentation. A four-grid Faraday cup was used to measure bulk velocity (V_b), ion density (N_0), ion temperature (T_i) and plasma flow direction by using the spacecraft spin. When the modulated second grid voltage V_{G_2} becomes equal to the potential, $m_i/2e (V_b \cos \theta)^2$, which is the energy corresponding to the component of the incoming ion bulk velocity normal to the electrode plane, then the ion flux starts to be modulated. Here, θ is the angle which is normal to the electrode with respect to the solar-wind stream. For example, when ions with bulk velocity 400 km s^{-1} (corresponding to a proton energy of 830 eV) and with $T_i = 0$ move towards the second grid to which a potential of $V_{G_2} = 490 \text{ V}$ is applied, the incoming ions are not retarded by the potential so long as the electrode surface faces the solar-wind stream. When θ becomes 40° as the Faraday cup rotates and the velocity component of the ions normal to the electrode plane becomes equal to V_{G_2} , the ions start to be retarded. Therefore the bulk velocity V_b can be obtained if the angle at which modulated ion current starts to appear at the collector is known and V_{G_2} monitored. The ion density is obtained from the collector current intensity. When T_i is finite, T_i , N_0 and V_b are obtained by fitting the measured curve to the one which is theoretically described by

$$I_{\text{out}} = \sqrt{\alpha/\pi} N_0 S_0(\theta) e \left\{ V_b \xi \int_{-V_b \xi}^{W-V_b \xi} e^{-\alpha t^2} dt + \frac{1}{2\alpha} (e^{-\alpha V_b^2 \xi^2} - e^{-\alpha (W-V_b \xi)^2}) \right\}$$

where $\alpha = m_i/2kT_i$, $W = \sqrt{2eV_{G_2}/m_i}$, $\xi = \cos \theta$, k is the Boltzmann constant, e the charge of electrons and $S_0(\theta)$ is the ion collecting area. Measurement of the current, of the order of 10^{-12} A , with proper frequency response is not an easy task under high-voltage operation.

The Faraday cup consists of four grids and an ion collector. The first grid is grounded to the satellite skin. A square wave

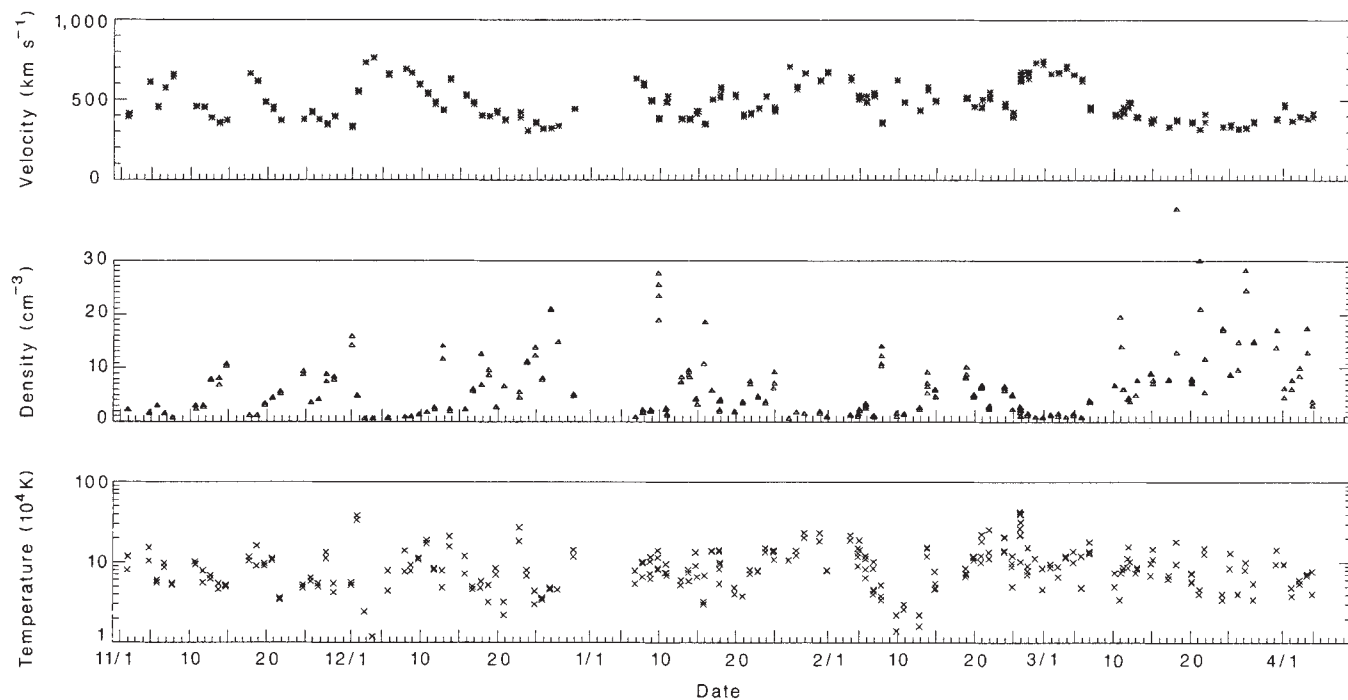


Fig. 1 Daily variation of the solar-wind parameters during the period 1 December 1985–1 April 1986.

is applied to the second grid to modulate incoming ions. The third grid is grounded to protect the leakage of high-voltage signal across the second grid. The fourth grid is biased to -100 V to suppress the emission of photoelectrons from the collector. The diameter of the collector is 100 mm and the distance between the first grid and the collector is 40 mm. The overall transparency of the four grids is 24%.

Background parameters. Figure 1 shows the diurnal variation of the solar-wind parameters as measured by Sakigake around the encounter dates of the six Halley probes. The solar-wind velocity gradually decreased during the period 3–7 March. No observation was carried out 8 and 9 March because Japan's second Halley probe Suisei required the use of a 64-m antenna which cannot receive the signal from both probes at the same time. The solar-wind speed was 400 km s^{-1} on 10 March and started to increase on 11 March. After peaking on 12 March, the solar-wind speed again decreased to a constant value of around 350 km s^{-1} . No data were generated on 14 March, as Sakigake's transmitter was switched to ranging mode to support Giotto. Since 15 March the velocity has remained constant at 350 km s^{-1} .

After 14 March, the 27-day cycle in solar-wind parameters seems to have completely disappeared. The closest approach of Sakigake to comet Halley occurred just before the small 'hump' in solar-wind velocity which occurred on 11 March as discussed below.

Closest approach. Figure 2 shows the plasma parameters measured around the closest approach. The data are from 12 h between 20:00 UT on 10 March and 08:19 UT on 11 March. From 21:42 UT on 10 March, the solar-wind velocity gradually increases, as predicted in advance from past solar-wind measurement assuming 27-day periodicity. The velocity remains nearly constant at 440 km s^{-1} , but with a very gradual increasing trend until 23:17 UT, when the first sudden change in solar-wind velocity occurs—a rapid deceleration. Solar-wind velocity then again starts to increase, reaching 450 km s^{-1} at 02:00 UT. A second sudden change in solar-wind velocity occurs at this time, a decrease of 20 km s^{-1} . This point corresponds to the region in which a strong plasma wave is detected. The wave experiment³ aboard Sakigake had not detected such a strong wave since its launch. The total strength of the interplanetary magnetic field

at this point increases from 5 nT to 8 nT. After the sudden drop at 02:00 UT, the solar-wind velocity gradually increases until 04:41 UT at a rate of increase of 20 km s^{-1} in 2 h 41 min. The third change occurs at 04:41 UT. Between 04:41 UT and 06:00 UT, the solar-wind speed is 440 km s^{-1} . From 06:00 UT the solar-wind speed decreases at a rate of 10 km s^{-1} per h until 07:05 UT. After 07:05 UT, it increases from 435 km s^{-1} to 447 km s^{-1} , then suddenly at 07:42 UT the speed drops to 420 km s^{-1} , the fourth drastic change of the solar-wind velocity.

Each step of the solar-wind change is associated with a decrease of ion density (N_o); at the first step, corresponding to 23:12 UT, N_o decreases from 18 ions cm^{-3} to 16 ions cm^{-3} , and at the second step at 02:00 UT, N_o decreases from 16 to 5 ions cm^{-3} . The third and fourth changes in solar-wind velocity are associated with spiky ion density increases. At 04:16 UT, N_o increases from 5 ions cm^{-3} to 10 ions cm^{-3} , corresponding to the region where the solar-wind velocity changes from 445 km s^{-1} to 452 km s^{-1} and also to the change of interplanetary magnetic field⁴. The IMF decreased to 5.6 nT during this period, 2.4 nT below ambient field intensity. At 07:12 UT the solar-wind speed starts to increase from 435 km s^{-1} to 447 km s^{-1} , and ion density suddenly increases from 4 to 12 ions cm^{-3} , remaining constant for 29 min, and falling back to 5 ions cm^{-3} . During this period, the IMF again decreases from 8 to 1.5 nT. Ion temperature changes are roughly in parallel with changes in solar-wind velocity, but at 04:41 UT the change in ion temperature is not as large as might be expected from the change in solar-wind velocity. Plasma flows slightly from the east (from the right-hand side of the Sun–comet line, looking towards the Sun) before 04:41 UT. There is a tendency for the plasma flow to make a smaller angle with the Sun–comet line as Sakigake approaches the comet, suggesting that the plasma flow may be distorted by the comet.

Discussion. The behaviour of the plasma parameters during the fly-by of comet Halley appears to be different from that observed before the encounter. The decreases of solar-wind speed at 23:12, 02:12, 04:41 and 07:42 UT occur during a phase of increasing solar-wind velocity predicted from the past 27-day periodicity of the solar-wind parameters. Superimposed on this trend is a gradual decrease of solar-wind velocity between 06:00 and

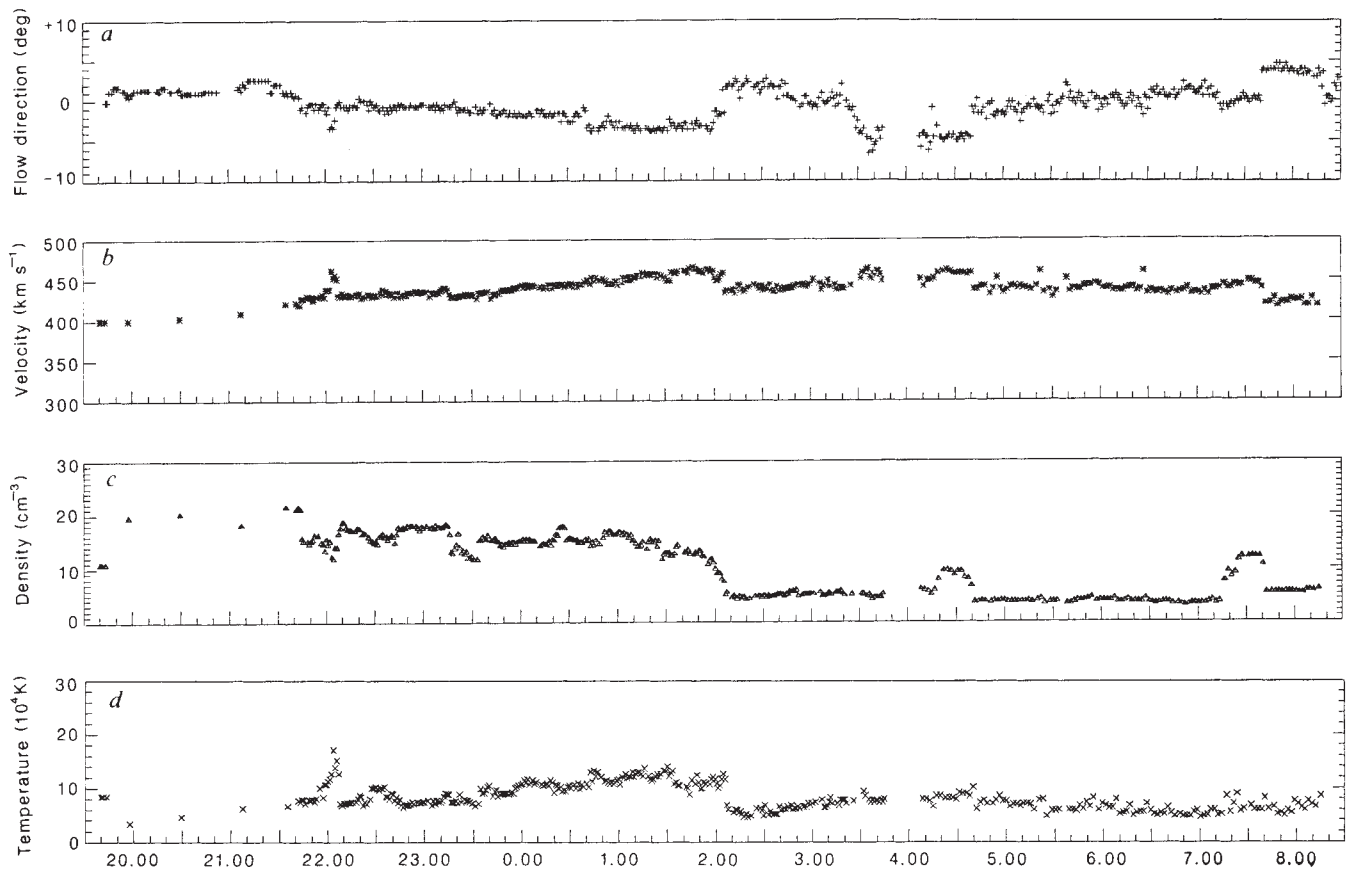


Fig. 2 Solar-wind parameters on the day of the Halley encounter. *a*, Flow direction; *b*, wind velocity; *c*, ion density; *d*, ion temperature.

07:05 UT. This period corresponds to the region where the x component of IMF falls to 3 nT. Further, during this period the wave experiment detected a plasma wave³. From these facts we deduce that the solar wind is more markedly decelerated in the region close to the comet. Figure 3 appears to show this situation. The steep reduction in solar-wind velocity between 04:00 and 22:00 UT on 11 March is nearly symmetrical with respect to the Sun-comet line. This means that maximum reduction of the solar-wind velocity occurs in front of the comet but not at the closest approach at 04:17 UT.

It is also noteworthy that the plasma flow direction is symmetrical with the Sun-comet line. The maximum deceleration of solar-wind velocity at this point is estimated to be $10\text{--}20\text{ km s}^{-1}$.

According to Biermann *et al.*⁵, the radius in which the effects of Halley's comet can be detected is likely to extend more than $1 \times 10^6\text{ km}$ from the comet's nucleus. Smith and co-workers⁶, using magnetic field measurements, showed that the influence of comet Giacobini-Zinner could indeed be detected at a distance of at least $1 \times 10^6\text{ km}$. Further, Ipavich *et al.*⁷ reported that energetic ions of cometary origin were observed as early as 15:00 UT on 11 September 1985, when the spacecraft (ICE) was some $1.5 \times 10^6\text{ km}$ from closest approach. Therefore, since comet Halley is much bigger than Giacobini-Zinner, it does seem possible that an influence of comet Halley might be detected at a distance of $7 \times 10^6\text{ km}$. On the other hand, the Suisei probe found no evidence of solar-wind deceleration after an approach at a distance of 400,000 km. The difference between the findings from Sakigake and Suisei could be due to differences in interplanetary magnetic field configuration.

Another factor may affect the behaviour of solar-wind parameters during the encounter. It is clear from IMF data that the Sakigake probe was near the solar current sheet. Between 04:00 and 19:00 UT on 10 March, Sakigake crossed a sector boundary.

The neutral sheet crossing occurred more than twice between 21:00 and 24:00 UT on 10 March. At 02:05 UT on 11 March the field intensity increased to 8 nT from the previous 5 nT. Sakigake presumably goes outside the solar plasma sheet of the heliomag-

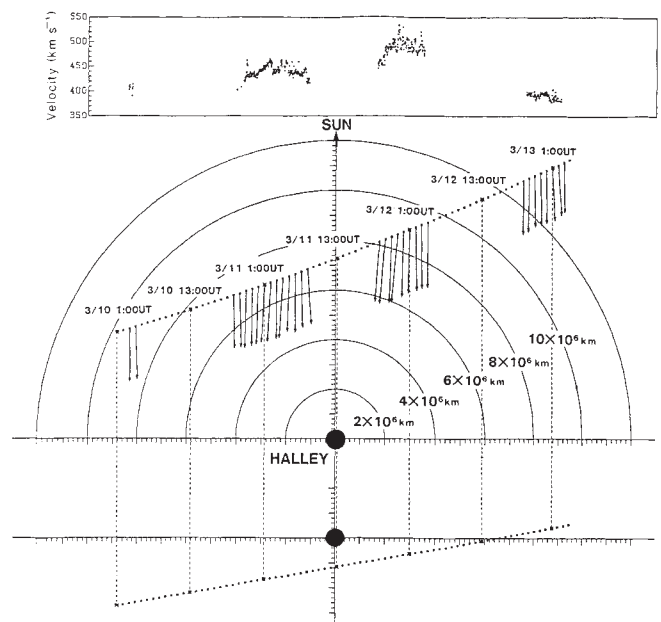


Fig. 3 Solar-wind velocity and flow direction during closest approach along the trajectory of Sakigake (comet Halley centred). Velocities and flow directions every 1 h. At the top of the figure, solar-wind velocities are plotted relative to a baseline of 350 km s^{-1} . Scattering of the data reflects a real variation.

netosphere (or inside the magnetic cloud) at 02:05 UT. Between 04:15 and 04:42 UT, and between 07:15 and 07:40 UT, the magnetic field intensity is 2 nT smaller than before and after these time periods. At these times the probe is in a region where an ion density increase was found, so it appears that ion density and field intensity change out of phase with each other. This behaviour is similar to the relationship between geomagnetic field and behaviour of charged particles in the plasma sheet in

the Earth's magnetosphere. Although the solar-wind parameters, IMF data and wave experiment do suggest an effect of comet Halley on interplanetary plasma at these distances, further studies are required to establish whether Sakigake detected a cometary effect on solar-wind speed, or whether the changes were independent of the comet and merely coincided with Sakigake's fly-by.

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The Giotto encounter with comet Halley

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The Giotto spacecraft encountered comet Halley on 14 March 1986, approaching to within ~600 km of the nucleus. Its scientific payload comprised ten hardware experiments: a narrow-angle camera, three mass spectrometers (for neutrals, ions and dust), various dust detectors a photopolarimeter and a set of plasma experiments. All experiments performed well and returned a wealth of new scientific results, of which perhaps the most important was the clear identification of the cometary nucleus.

AN encounter with a comet was perhaps the last purely exploratory mission left in Solar System studies. Very little was known about the most active members of our Solar System; for example, we could only speculate about the existence and size of a body (the comet nucleus) which near perihelion can produce a hydrogen corona larger than the Sun. Although comets had been observed for centuries, our knowledge remained limited to the determination of cometary orbits, phenomenological descriptions of the comae and tails, and analysis of cometary spectra. Observations of comets from Earth (ground-based or from near-Earth space) can provide only line-of-sight integrations, and are restricted to molecules with strong emission lines in suitable wavelength ranges. In particular, the neutral parent molecules released from the nucleus can be detected only by *in situ* measurements, which can reveal the complex physical and chemical processes in the cometary atmosphere.

It is generally assumed that comets were formed at the time of formation of the Solar System, 4.6×10^9 years ago, and that $\sim 10^{12}$ comets exist in a vast cloud around the Sun (the 'Oort cloud') at a distance of $\sim 50,000$ AU. Once every 10 million years, on average, a passing star in the distant reaches of the Solar System gives rise to gravitational perturbations which cause a number of comets to be deflected into the jovian capture region (4-6 AU from the Sun). Occasionally, the orbit of such a comet is then perturbed into a short-period orbit by the gravity of one of the major planets.

Our knowledge of comets comes from the fact that the nucleus, although generally too small to be observed from the Earth, becomes active as it approaches the Sun. Heated by insolation, the nucleus releases large amounts of gas and dust during its passage through perihelion. This unpredictable and often violent process produces an atmosphere of enormous extent. Neutral molecules, some highly reactive, are formed by sublimation and expand to distances of 10^5 - 10^7 km. Ionized molecules, produced by photoionization and probably also by electrons, have on occasion been observed even in the inner parts of this atmosphere. In addition, ions are accelerated out of the central region to form a narrow, straight plasma tail in the anti-solar direction.

Such a tail shows visual evidence of complex hydromagnetic phenomena (filaments, rays, kinks and helices).

The gas streaming out of the nucleus carries with it quantities of fine dust. At distances of $\sim 10^4$ km from the nucleus, solar radiation pressure exceeds the aerodynamic drag force on the dust, which is then swept out of the comet's atmosphere to form the dust tail. Because the velocities of the dust particles cover a wide spectrum, corresponding to the wide spectrum of dust particle sizes, the dust tail is broad and curved. What is visible and known as the 'comet' is in fact sunlight scattered by the dust particles and line emission from neutral particles and ions excited by sunlight (fluorescence).

The cometary nucleus is thought to consist of a mixture of dust and ice; mainly water ice, but also many other ices composed of H, C, N and O. The dimensions and mass of most cometary nuclei are inferred to be in the ranges 1-10 km and 10^{15} - 10^{18} g, respectively. As a result, the gravitational attraction is minute (escape velocity only 1 - 5 m s $^{-1}$) in comparison with that typical of planets. The absence of external heating and of heating by self-gravitation should lead to a composition which is qualitatively different from those of all other bodies in the Solar System, and which may preserve the elemental abundances and isotopic ratios characteristic of the early Solar System.

Up to now, around 1,000 different comets have been recorded, and the rate of new discoveries is 5 to 10 per year. Based on their orbital periods, comets can be categorized as short-period (with periods between 3 and 25 yr), intermediate-period (25-200 yr), long-period (200- 10^6 yr) and 'new' comets; that is, comets that have never previously approached the Sun. Halley with its 76-yr period belongs to the category of intermediate-period comets.

The most active and therefore brightest comets are the new ones; however, they are not suitable candidates for a spacecraft encounter. To plan a mission to a comet its orbit must be well known, which means that it must have returned at least a few times. This rules out new comets and leaves only the short-period and a few intermediate-period comets as potential targets.

Short-period comets are not very bright. On average, they

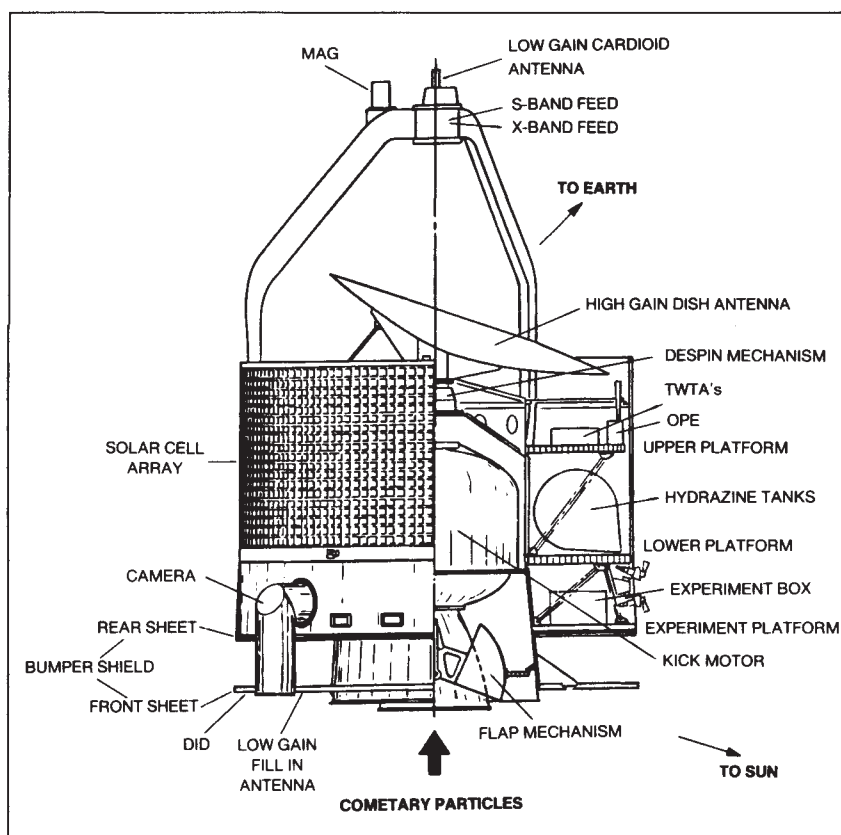


Fig. 1 A cross-section through the Giotto spacecraft.

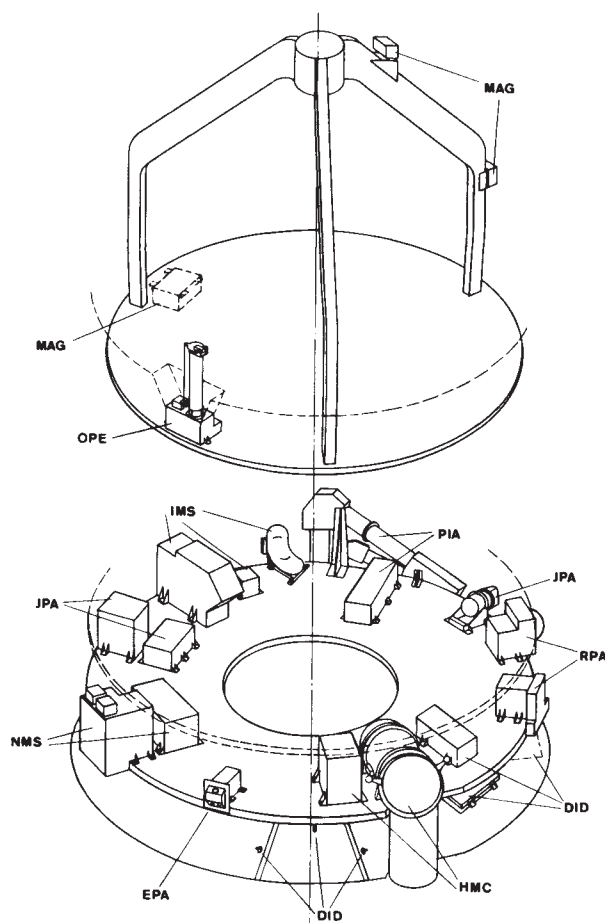


Fig. 2 Positioning of Giotto's experiments on the spacecraft structure. The experiment acronyms are listed in Table 1.

produce 100 times less gas and dust than new comets, presumably because they accumulate thick dust layers on their surface. Halley is the only one of the ~1,000 recorded comets which has both a well-known orbit—it has been observed at each apparition since 240 BC—and high gas and dust production rates, comparable to those of new comets. Moreover, a mission to comet Halley requires one of the lowest launch energies of all possible cometary missions and, finally, Halley could be seen from Earth during the fly-by, thus enabling correlation of the *in situ* measurements with remote ground-based observations.

Halley is thus an outstanding target for a first cometary mission, and this is why in July 1980 the Science Programme Committee of the European Space Agency (ESA) selected it as the target for a first cometary mission. The mission was named 'Giotto' after the Italian painter Giotto di Bondone, who in 1304 depicted comet Halley as the 'star of Bethlehem' in one of the frescoes in the Scrovegni chapel in Padua.

Giotto and its scientific payload

The Giotto mission to comet Halley was ESA's first interplanetary mission, and Giotto was ESA's first scientific spacecraft to be launched by an Ariane rocket.

The spacecraft (Fig. 1) is spin-stabilized, with a nominal spin period of 4 s. Its diameter is 1.86 m, and the height from the tip of the tripod to the bottom adaptor ring is 2.85 m. At launch Giotto weighed 960 kg, reducing to 573.7 kg at closest approach after the solid-propellant kick motor used to inject the spacecraft from a geostationary transfer orbit into a heliocentric orbit had burnt out, and 9 kg of the available 69 kg of hydrazine had been used for three orbit manoeuvres and a large number of attitude corrections.

Because Halley's orbit is retrograde, that is, of opposite sense to those of the Earth and the spacecraft, the encounter velocity is very high (68.4 km s^{-1}). Compared with this, the speed of the cometary gas and dust particles is very low (a few hundred metres per second). Giotto thus saw an essentially static situation

Table 1 Giotto scientific payload

Experiment (acronym)	Mass (kg)	Data rate (bits s ⁻¹)			Goal and instrument parameters	Ref.
		F1*	F2†	F3‡		
Camera (HMC)	13.51	20,058	20,058	723	Inner coma and nucleus imaging, CCD§ narrow-angle camera, 11-m resolution from 500 km	6
Neutral mass spectrometer (NMS)	12.70	4,156	4,156		Neutral gas composition	7
M-analyser					M-analyser: 1–36 AMU	
E-analyser					E-analyser: 1–57, 9–89 AMU	
Ion mass spectrometer (IMS)	9.00	3,253	3,253	1,084	Ion composition	8
High-energy-range spectrometer (HERS)					HERS: 1–35 AMU/q	
High-intensity-range spectrometer (HIS)					HIS: 12–57 AMU/q	
Dust mass spectrometer (PIA)	9.89	2,891	5,782		Dust particle flux and composition, 1–110 AMU, 3×10^{-16} – 5×10^{-11} g	9
Dust impact detection system (DID)	2.26	361	903		Dust particle flux and mass distribution	10
Meteoroid shield momentum sensor (MSM/RSM)					IPM: 6×10^{-17} – 6×10^{-11} g	
Impact plasma and momentum sensor (IPM)					CIS: $>10^{-10}$ g	
Capacitor impact sensor (CIS)					MSM/RSM: 10^{-10} – 10^{-1} g	
Plasma analysis 1 (JPA)	4.70	3,975	1,265	1,355	FIS: 3-dimensional ion velocity distributions, 10 eV–20 keV	12
Fast ion sensor (FIS)					IIS: ion flux, mass and velocity distributions, 90 eV–90 keV, 1–45 AMU/q	
Implanted ion sensor (IIS)						
Plasma analysis 2 (RPA)	3.21	2,530	1,807	904	EESA: 3-dimensional electron velocity distributions, 10 eV–30 keV	14, 17
Electron electrostatic analyser (EESA)					PICCA: composition of cold ions, 10–50 AMU, 50–203 AMU	
Positive-ion cluster composition analyser (PICCA)						
Energetic particle analyser (EPA)	0.95	181	181	181	Energy and flux of electrons and accelerated ions, ≥ 20 keV	13
Magnetometer (MAG)	1.36	1,265	1,265	407	Magnetic field, 0.004–65,536 nT, up to 25.4 vectors s ⁻¹	15
Optical probe experiment (OPE)	1.32	723	723		Coma brightness in 4 continuum bands (dust), 4 discrete emissions (OH, CN, CO ⁺ , C ₂)	18
Radio-science experiment (GRE)					Dust and gas column densities in the coma	11
Total	58.90	39,393	39,393	4,654		

* Format 1, from switch-on until –1 h and after +1 h ($t=0$ at time of closest approach).

† Format 2, from –1 h to +1 h.

‡ Format 3, during cruise phase.

§ Charge-coupled device.

as it traversed the coma, and all particles struck the spacecraft from the forward direction. During the Halley encounter the spacecraft spin axis was aligned with the relative velocity vector ('relative' means in the comet's frame of reference); that is, the cometary particle streaming was from below in Fig. 1. A dust particle with a mass of only 0.1 g and a velocity of 68 km s⁻¹ can penetrate an aluminium sheet 8 cm thick. Protection of the spacecraft from high-velocity dust particle impacts was thus essential for the spacecraft to approach to within a few hundred kilometres of the nucleus, where dust fluxes are high. Giotto carries a dual-sheet bumper shield, consisting of a thin front sheet and a thick rear sheet, separated by a large gap. A dust particle striking the thin front sheet is completely vaporized: the vapour cloud then expands into the empty space between the two sheets and strikes the rear sheet, where its energy is dissipated by being distributed over a large area. It had been calculated that the shield could withstand the impact of dust particles of mass up to ~ 1 g.

At the other end, well protected from dust particle impacts, Giotto carries a high-gain antenna with an effective reflector diameter of 1.47 m. This antenna can be operated in either the S-band (receiving at 2.1 GHz, transmitting at 2.3 GHz) or the X-band (transmitting at 8.4 GHz). The antenna beam is inclined 44.3° with respect to the spacecraft spin axis and the antenna itself is despun, so that the beam could point continuously at

the Earth during the encounter. The pointing requirements in the X-band are rather stringent: if the antenna beam were to be misaligned by more than 1° the telemetry link to the ground receiving station would be lost. It was calculated before the mission that the impact of a 0.1-g dust particle on the rim of the bumper shield could change the spacecraft attitude and hence the antenna pointing direction by more than 1°.

Giotto's scientific payload comprises 10 hardware experiments (Table 1) with a total mass of just under 60 kg: a camera for imaging the comet nucleus and inner coma, three mass spectrometers for analysing the elemental and isotopic composition of cometary neutrals, ions and dust particles, various dust impact detectors, a photopolarimeter for measuring the coma brightness, and a set of plasma experiments for studying the interaction processes between the solar-wind plasma and the cometary ionosphere. All experiments are mounted on the 'experiment platform' of the spacecraft (see Fig. 2), with the exception of the dust impact detectors which are mounted on the outer face of the bumper shield, the two magnetometer sensors which are mounted on the tripod, and the photopolarimeter which is mounted near the high-gain antenna, looking rearward. All other experiments look in the forward direction (downward in Fig. 1), apart from some plasma experiments which look to the side, to observe the changing characteristics of the solar-wind plasma. Giotto has no on-board data storage

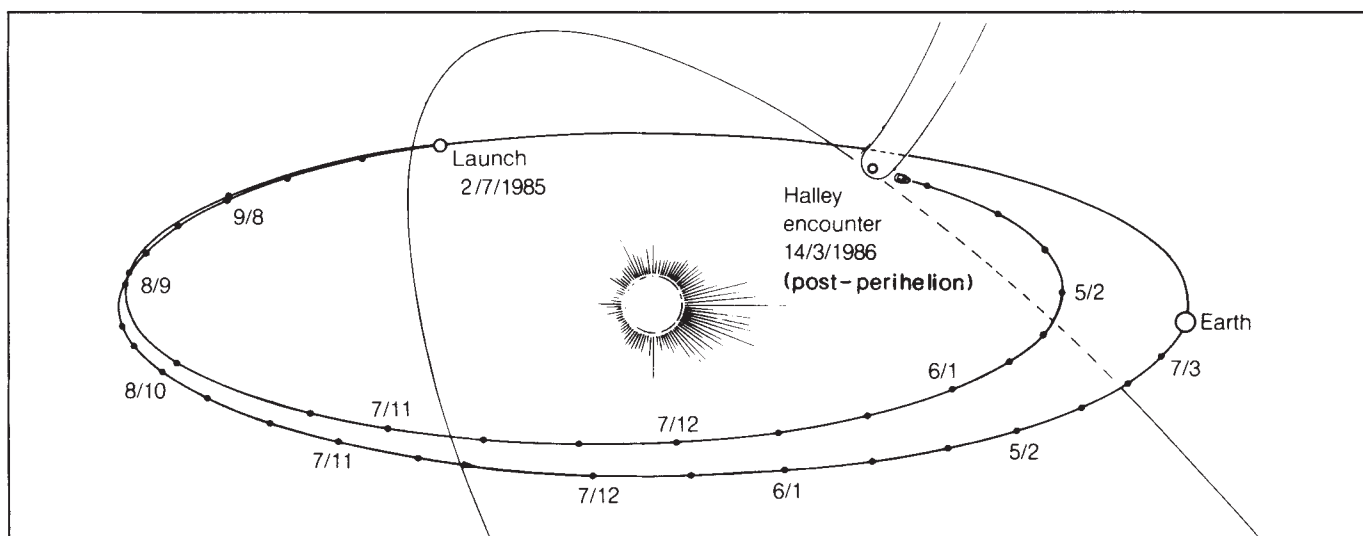


Fig. 3 Interplanetary trajectory for Giotto from launch on 2 July 1985 until closest approach to comet Halley on 14 March 1986.

capability; all data are transmitted in real time. Two experiments (MAG and EPA; acronyms are defined in Table 1) have small memories to bridge gaps in ground-station contact during the cruise phase. As Giotto traverses the coma it is decelerated by gas and dust impacts; the Radio-Science Experiment was designed to measure this deceleration by observing the Doppler shift of the Giotto radio signal, and to derive from it the dust column density along the Giotto trajectory. Detailed experiment, spacecraft and mission descriptions can be found in refs 1 and 2.

The encounter

After five years of development and testing, Giotto was launched on 2 July 1985 by an Ariane-1 rocket from Kourou, French Guyana. Figure 3 shows the interplanetary trajectory for Giotto from launch until closest approach. The trajectory lies in the ecliptic, with a closest approach to the Sun of 0.72 AU, reached on 31 December 1985. Halley's retrograde orbit is also shown, with its orbit plane inclined by 18° with respect to the ecliptic.

For the routine operation of the spacecraft in the S-band, ESA's ground station at Carnarvon, Australia, was used, and the 64-m ground station at Parkes, Australia, was used for high-rate transmission of scientific data (Format 1 or 2, Table 1). The Parkes antenna is owned and operated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and is normally used for radioastronomy. In addition, scientific data were transmitted to Carnarvon and the West German Weilheim station at low rate (Format 3) a few times per week during the cruise phase. During the encounter, the 64-m station at Canberra, operated by the U.S. National Aeronautics and Space Administration (NASA), was kept in instant readiness. Continuous data coverage for ~ 70 h before and ~ 30 h after closest approach in high-data-rate mode was provided by the Parkes ground station together with the NASA 64-m Deep Space Network (Goldstone, Madrid, Canberra).

The spacecraft was targeted to fly past the nucleus at a closest distance of (500 ± 40) km on the sunward side, 40 km being the combined 1σ uncertainty of the spacecraft and Halley nucleus positions³. This distance was chosen as a compromise between the partially conflicting requirements of three groups of experiments. The camera (HMC) experimenters wanted to fly past ideally at 1,000 km, but no closer than 500 km. A second group (OPE, MAG, NMS, IMS) wanted to approach as close as possible to the nucleus, even if the spacecraft did not survive, and a third group (PIA, DID, EPA, JPA, RPA) also wanted to approach as close as possible, while maintaining a high survival probability. The fly-by distance that was actually achieved was 600 km, as derived independently from camera observations (variation of the camera offset angle with time) and spacecraft

orbit determination from the ground (ranging). All relevant encounter parameters are summarized in Table 2. The time of closest approach was $00:30:01 \pm 2$ s UT. (A more precise time will be established in future.) This time is given as 'spacecraft event time' (SCET); however, some experimenters prefer to use 'ground-station received time' (GSRT). The two are related by: $GSRT = SCET + 8 \text{ min } 0.1 \text{ s}$.

Although Giotto was targeted relatively close to the nucleus where the dust fluxes are high, the spacecraft was expected to survive. This expectation was based on spacecraft attitude perturbation calculations, assuming a model in which dust particles are emitted homogeneously over the nuclear surface towards the Sun⁴. Although dust jets were known to exist⁵, neither their exact location nor their temporal activity pattern could be specified. (Dust jets are regions of the coma in which the flux of $1\text{--}10\text{-}\mu\text{m}$ dust particles is enhanced by a factor of 3–10, making the jets appear brighter than the ambient coma.) Evidently, if Giotto were to enter a dust jet it would be unlikely to survive—the large particles associated with these regions are difficult to avoid. As their outflow velocities are small (a few tens of metres per second) and the Halley nucleus rotates with a period of 52 h, the regions form tight spirals around the nucleus.

Fourteen seconds before closest approach Giotto was hit by such a 'large' dust particle. The impact caused the spacecraft angular momentum vector to shift by 0.9° , and the spacecraft performed a nutation around the new axis with a period of 16 s and an amplitude of 0.9° ; thus, the maximum deviation from

Table 2 Parameters at closest approach

Distance to comet nucleus	
From orbit determination	610 ± 40 km
From camera observations	605 ± 8 km
Distance to Earth	1.44×10^8 km
Distance to Sun	1.35×10^8 km
Time of closest approach (spacecraft time)	
As derived from orbit determination	$00:03:00.4 \pm 2$ s UT
As derived from camera observations	$00:03:02 \pm 1$ s UT
Phase angle (Angle between the spacecraft velocity in the comet frame of reference and the Sun-Comet line)	107.05°
Angle between the Sun-comet line and the spacecraft-comet line	$29.3^\circ \pm 0.3^\circ$ (south)
Spacecraft velocity in the comet frame of reference	68.373 km s^{-1}
Spacecraft spin period	
Before dust impact	3.998 s
After dust impact	4.010 s

the desired attitude was 1.8° . As had been expected in such an event, the telecommunications link to Earth could not be maintained continuously: scientific data were received intermittently for the next 32 min. By that time the on-board nutation dampers had reduced the maximum deviation from the desired attitude to $\leq 1^\circ$ and continuous data were again received. Because the dust protection system provides protection against incident dust particles only if the deviation of the spacecraft spin axis from the relative velocity vector is $\leq 1^\circ$, some experiment sensors suffered damage during this 32-min interval. Other experiments (camera baffle and deflecting mirror, DID sensors on the front sheet of the bumper shield, most experiment apertures) were exposed to dust particles even without the attitude perturbation and also suffered damage. The status of each experiment after the fly-by is given in Table 3.

Although the spacecraft itself suffered some damage during the fly-by (solar-cell-array power output reduced from 196 to 191 W, star-mapper baffle performance and thermal control subsystem degraded), it was possible to re-target it to return to the neighbourhood of Earth on 2 July 1990. Using an Earth gravity assist (fly-by at 22,000 km), it could be redirected towards comet Grigg-Skjellerup for an encounter on 14 July 1992.

First results

Cometary nucleus. The images⁶ revealed a single nucleus of elongate, non-spherical shape (like a potato) in the centre of the comet. The major axis is ~ 15 km, the minor axis 7–10 km. The length of the minor axis is rather uncertain, as it is directed sunward, and the sunward side is partially obscured from view by dust; however, the nucleus is clearly larger than had been anticipated⁴ (predicted diameter 6 km). The nucleus surface is irregular and shows spherical structures, not unlike impact craters, and valleys and hills. The nucleus has a very low albedo (2–4%), comparable to the darkest bodies in the Solar System: presumably it is covered with a layer of dust.

Two major, bright dust jets emanate from the sunward side of the nucleus. The maximum brightness is probably close to the nucleus, where the dust number density is high because particles are being accelerated from zero velocity to their terminal velocities, which are not reached until a distance of a few nuclear radii. Most of the cometary activity appears to originate from only a few discrete sources on the nucleus. A rotation period and a spin axis could not be derived from the images.

Neutral particles. NMS⁷ revealed that, as expected, H_2O is the dominant parent molecule in the Halley coma⁷. At the time of the Giotto encounter the total gas production rate was 6.9×10^{29} molecules s^{-1} , with an uncertainty of $\pm 50\%$, of which 5.5×10^{29} molecules s^{-1} ($\sim 10^7$ g s^{-1}) was water vapour production. The radial gas outflow velocity was derived, along with upper limits for the $\text{CO}_2/\text{H}_2\text{O}$, $\text{NH}_3/\text{H}_2\text{O}$ and $\text{CH}_4/\text{H}_2\text{O}$ volume mixing ratios.

Ions. In its ion mode, NMS⁷ unambiguously identified a number of ions and measured their directional and energy distribution.

IMS⁸ observed cometary H^+ ions well outside the bow shock in a diffuse shell-like distribution. Inside the bow shock the heavier ions C^+ , H_2O^+ , CO^+ and S^+ showed similar distributions. Closer to the comet H^+ , He^+ , C^+ , O^+ , OH^+ , H_2O^+ , H_3O^+ , CO^+ and S^+ were observed. Inside the contact surface very low ion temperatures and outflow velocities of ~ 1 km s^{-1} were found. The spectra show a striking richness in C^+ which cannot be accounted for by photodissociation of CO , CH_4 and CO_2 to C followed by photoionization of C . Perhaps carbon atoms are released directly at the surface, or the source may be the dust grains themselves.

Dust. Preliminary analysis of spectra recorded by PIA⁹ shows the presence of H, C, N, O, Na, Mg, Si, K, Ca and Fe. Most of the dust particles are rich in H, C, N and O. In contrast to expectations, the mass spectra generally indicate that a type C1 carbonaceous chondrite composition only partially fits cometary particles.

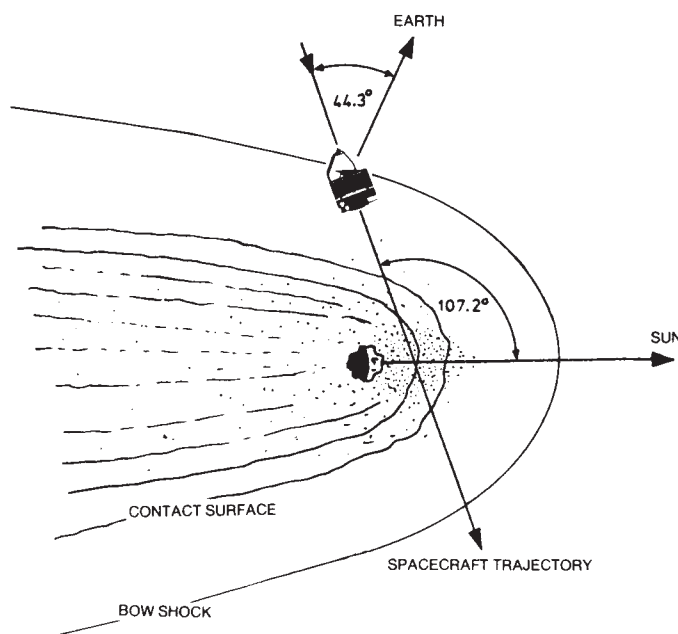


Fig. 4 Schematic of the encounter geometry. Giotto passed the nucleus at a distance of 600 km on the sunward side. The bow shock was crossed at 1.15×10^6 km; the contact surface was crossed at 4,700 km from the nucleus.

The first dust particle impact was recorded by DID¹⁰ at a distance of 290,000 km from the nucleus, further away than expected by dust models. In all, 12,000 dust particle impacts were recorded, ranging in mass from 10^{-17} to 1.4×10^{-4} g. The total dust production rate derived from measurements shortly before closest approach was 3.1×10^6 g s^{-1} . The observed dust size spectrum at 2,200 km from the nucleus can be approximated by a power law with index -2.98 ± 0.15 , which corresponds to -3.48 ± 0.15 for the spectrum of dust particles released from the nuclear surface. This is significantly flatter than predicted by models; also, in contrast to expectations, there is no indication

Table 3 Health of the Giotto payload after the Halley encounter

Expt	Damage assessment	Functional
HMC	Mirror degradation Baffle perforation Needs further investigation	?
NMS	CCDs of both detectors dead Stopped working at 00:10:50.4 UT (ground-station received time)	No
IMS	HERS: high-voltage damage HIS: no damage	No Yes
PIA	No damage	Yes
DID	MSM: no damage CIS: recovered	Yes Yes
JPA	IPM: shows anomalous behaviour FIS: stopped working at +1.5 h IIS: no damage	No No Yes
RPA	EESA: inlet damaged by dust impacts (2 parts in close contact, corona effect) Reduced performance (electron density fine, distributions distorted) PICCA: high-voltage problem, needs further investigation	50% ?
EPA	No damage	Yes
OPE	No damage	Yes
MAG	No damage	Yes

of a decrease in the spectrum at masses $<10^{-14}$ g. The Radio-Science Experiment¹¹ measured a Doppler shift of 4.7 Hz in the Giotto radio signal. This shift corresponds to a deceleration of 23.2 cm s^{-1} caused by the drag effect of the cometary atmosphere during the fly-by. Bearing in mind the large uncertainties in the momentum multiplication factors (see ref. 10), the total cometary mass (mostly dust) intercepted by the spacecraft was determined to be 0.1–1 g.

Plasma. The interaction between the solar-wind plasma and the cometary ionosphere can be characterized by two distinct boundaries—the bow shock and the contact surface—and several additional sharp transitions, giving the impression of a multi-layered interaction region.

For several days before closest approach the solar wind was relatively quiet. Its flow speed was $\sim 350 \text{ km s}^{-1}$ and its density between 5 and 8 cm^{-3} . The first hydrogen ions of cometary origin (pick-up ions) were detected by JPA¹² at a distance of $7.8 \times 10^6 \text{ km}$ from the nucleus; EPA detected pick-up ions shortly afterwards, at $7.5 \times 10^6 \text{ km}$. Once cometary neutrals are ionized they are 'picked-up' by the solar wind. They spiral around the magnetic field and at the same time start to drift perpendicular to it ($\mathbf{E} \times \mathbf{B}$ drift). Their maximum velocity is twice the solar-wind velocity, and their minimum velocity is their original outward streaming velocity. The effect of the comet interaction on the solar-wind electron heat flux is clearly observed out to at least $7.5 \times 10^6 \text{ km}$ by RPA¹⁴. This flux is observed when a spacecraft is magnetically connected to a bounded, hotter and denser plasma source. Magnetic field variations resulting from the comet interaction were identified unambiguously¹⁵ at a distance of $2 \times 10^6 \text{ km}$, and less clearly further out.

At the time of the Giotto encounter the bow shock was located at a distance of $1.15 \times 10^6 \text{ km}$ from the nucleus, in good agreement with expectations (derived from scaling comet Giacobini-Zinner's bow shock distance with the higher Halley gas production rate). Inside the bow shock the solar-wind flow speed decreased to 260 km s^{-1} due to mass loading by cometary ions, and the flow was directed away from the usual radial outflow direction. At a distance of 16,400 km from the nucleus (this and the following distances have an uncertainty of a few hundred kilometres), the magnetic field strength reached a maximum of 57 nT (pile-up region). Inside the contact surface, which was crossed at a distance of 4,700 km before closest approach, the magnetic field dropped essentially to zero. This had been theoretically predicted and was expected by analogy with Venus and the 'artificial comet' of the AMPTE mission¹⁶. Giotto re-emerged from the field-free region $\sim 3,800 \text{ km}$ after closest approach. On the outbound leg the maximum field strength was observed to be 65 nT at a distance of 8,200 km from the nucleus. In contrast to the inbound pass, the evidence for an outbound bow shock was not very clear, as the decrease of magnetic field magnitude and fluctuations was much more gradual. Upstream waves resulting from the comet interaction could be observed until $\sim 2.7 \times 10^6 \text{ km}$ from the nucleus.

I thank the experimenters and the ESTEC and ESOC project teams for close collaboration throughout all phases of the mission; in particular, the Giotto project manager D. Dale for keeping us all on schedule, and J. Credland (ESTEC) and A. Parkes (ESOC) for their extremely hard and dedicated work.

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Pathfinder: accuracy improvement of comet Halley trajectory for Giotto navigation

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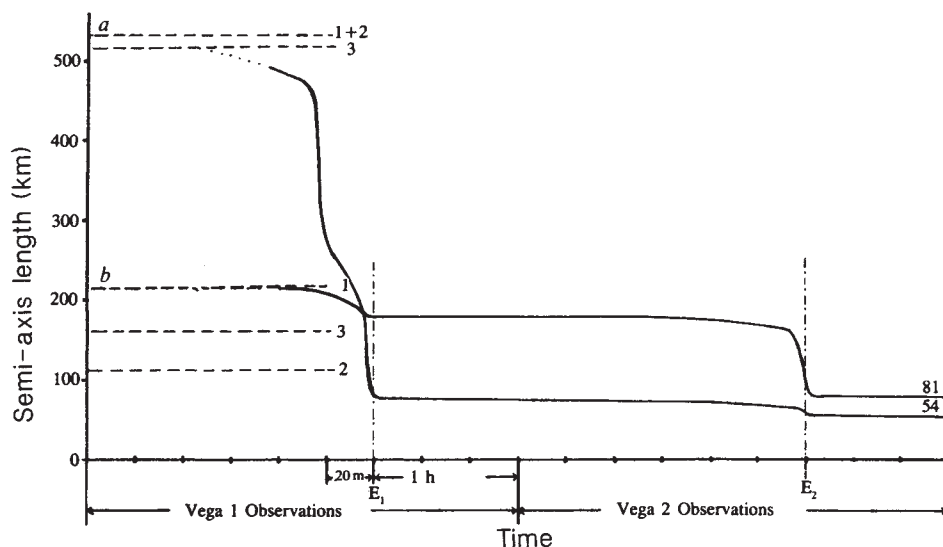
The 'Pathfinder' project represents a cooperative effort involving the space agencies Intercosmos (Soviet Union), the National Aeronautics and Space Administration (NASA; United States) and the European Space Agency (ESA; Europe) for the benefit of the Giotto mission, the context of which was the stringent requirement for Giotto to fly past comet Halley at a distance of $\sim 500 \text{ km}$ on the sunward side. The uncertainties^{1–5} in the comet's trajectory were such that this requirement could not be fulfilled with the necessary accuracy using only ground-based astronomical observations; early studies^{6–8,20} revealed that a considerable improvement could be attained by incorporating space-borne observations. As the two Vega spacecraft were to reach the comet a few days before Giotto, optical observations performed by the Vega cameras could be used for this purpose. These, combined with a very accurate determination of the Vega trajectories using VLBI (very-long-baseline interferometry)^{9,10}, permitted a final fly-by distance of 600 km to be achieved with an uncertainty of only $\pm 40 \text{ km}$ (1σ probability level).

An optical observation of comet Halley made from a terrestrial observatory at an approximate distance of 1 AU ($1.5 \times 10^8 \text{ km}$) will have a directional uncertainty, including the various sources of error, of $\sim 2 \text{ arc s}$. This angle is equivalent to a positional error of the comet at the time of observation of $\sim 1,500 \text{ km}$. This means that, neglecting the range, the comet is localized with this 1,500-km uncertainty (the additional error of the Earth position itself, being less than 10 km, is negligible). If we assume that an optical observation made by a space-borne observatory at a distance of 10,000 km from the comet has a directional uncertainty of $\sim 3 \text{ arc min}$ (as is the case for Vega), then translating this angle into a positional error yields a value of $\sim 10 \text{ km}$ (again neglecting the range). In this case, however, the uncertainty of the observatory position is far from negligible, dominating the cited 10 km by a factor of ~ 40 (there is an uncertainty of 400 km in the positions of the Vega spacecraft using conventional range and Doppler tracking techniques). It is evident that in this case the angular error is negligible compared with the influence of the uncertainty in the observatory location. Improved location of the observatory results in an improved determination of the comet's position.

The above discussion contains the essence of the 'Pathfinder concept'. It demonstrates that a dramatic improvement in accuracy can be expected from using space-borne observations when the spacecraft observatory can be located with high accuracy. In practice the following points need to be addressed:

(1) Viewing geometry. Ground-based and space-borne observations are purely directional, yielding no direct measure-

Fig. 1 Predicted gain in comet trajectory accuracy with the acquisition of information from Vega observations. The lengths of the semi-axes (a , b) of the 1σ uncertainty ellipse are plotted against time, relative to the times of closest approach for Vega 1 (E_1) and Vega 2 (E_2). The dramatic improvement occurs only a few minutes before the Vega 1 closest approach, at which time the semi-major and semi-minor axes reverse roles. Also shown (dashed lines) are the semi-axis lengths achievable by ground-based observations alone: 1, with system noise in the z direction; 2, without system noise; and 3, the International Halley Watch (IHW) baseline¹.



ment of distance. For navigational purposes, however, the trajectory of the comet (that is, the past and predicted time sequence of positions) is required. For this reason a series of directional measurements is needed with changing viewing geometry to solve for the unknown distance.

(2) Trajectory modelling. Determination of the comet's trajectory, and particularly its prediction, requires a physically realistic model of its motion including all forces acting on it. Gravitational forces generated by Solar System bodies are comparatively easy to model (the ephemerides of all planets are known very accurately). However, non-gravitational forces can be modelled only with some uncertainty. These forces result from the near-Sun outgassing and dust-emission effects which, rocket-like, change the comet's velocity^{11,12}.

(3) Measurement modelling. The gas and dust¹³ surrounding the comet nucleus render it essentially unobservable, introducing an uncertainty in the directional measurement; that is, a bias¹⁴ that represents the difference between the visual centre and the nucleus. As with the parameters in the model for the non-gravitational forces¹⁵, this bias must be determined during the orbit determination process.

All of the above considerations were taken into account in planning the Pathfinder project. Figure 1 summarizes the improvement in accuracy resulting from the use of Vega observations, according to studies using both covariance and simulation techniques⁶⁻⁸.

Starting in July 1985, after the two Vega spacecraft had finished their exploration of Venus, the first major component of the Pathfinder project was carried out for the precise determination of their trajectories. This determination was based on VLBI techniques, using two pairs of widely separated 64-m antennae, at the NASA Deep Space Network stations Madrid, Goldstone and Canberra, to receive simultaneously a wide-band signal broadcast by the spacecraft. Cross-correlation of the signal furnishes a precise measure of the differential time delay, which in turn determines the angle between the inter-station baseline and the spacecraft. By alternately tracking the spacecraft and a known extragalactic radio source (quasar) adjacent on the sky, a doubly-differenced measurement is performed to cancel out common error sources (synchronization of the station clocks). The exercise was performed for both Vega spacecraft until their encounters with the comet on 6 and 9 March 1986, and revealed a remarkable accuracy of better than the predicted 40 km (1σ) at the time of the encounters.

The second major Pathfinder component was started after the Vega 1 encounter, and used optical measurements of the direc-

tion from spacecraft to comet (later also carried out from Vega 2). Spacecraft telemetry is processed for the determination of the spacecraft inertial attitude (with the help of Sun sensor, star sensor and gyroscope data), the reconstruction of the moving camera-platform's position relative to the spacecraft, and the location of the comet nucleus in the camera's field of view by appropriate image processing techniques. For both Vega spacecraft these 'inertial angles' were obtained in the periods before and after closest approach, thus producing an excellent basis

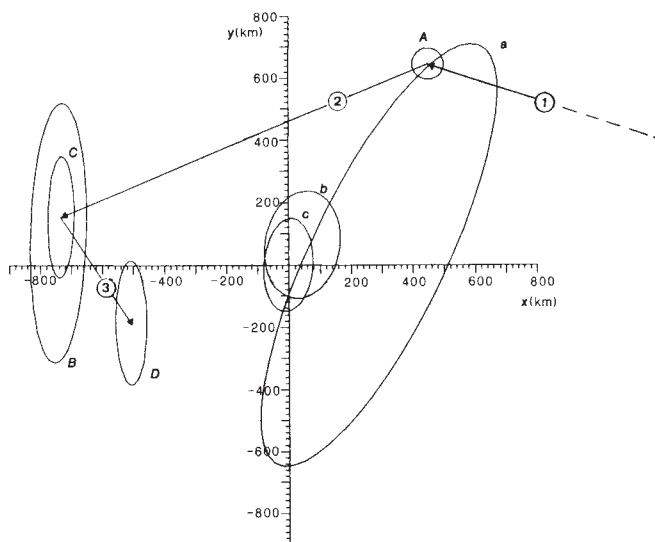


Fig. 2 Uncertainty ellipses (3σ) for comet Halley and Giotto. The ellipses shown are projections of the three-dimensional position uncertainty ellipsoids onto the Giotto target plane. This plane is defined by the position of the comet at closest approach (origin of the coordinate system) and by its normal, which is parallel to the spacecraft-comet relative velocity vector. The x -axis is the trace of the ecliptic; the y -axis points north. Ellipses a - c refer to the comet location (a , from International Halley Watch, 5 March 1986; b , from Vega 1 observations; c , from Vega 1 and Vega 2 observations); A - D to the target position (A , 27 August 1985; B , 5 March 1986; C , 12 March 1986; D , 14 March 1986). Three targeting manoeuvres were performed, the last one (1, August 1985; 2, February 1986; 3, 12 March 1986) 2 days before closest approach, based on Pathfinder results.

for the improvement in the determination of the comet's trajectory. Figure 2 illustrates this improvement and also shows the targeting process for the Giotto spacecraft, which was manoeuvred to the final target just 2 days before its closest approach to the comet on 14 March 1986, successfully using the results obtained by Pathfinder.

The Pathfinder project evolved out of work in the Inter-Agency Consultative Group (IACG), established in 1981 (ref. 21), which comprises Intercosmos, NASA, ESA, the Institute of Space and Astronautical Science (ISAS; Japan) and, as

representative, the International Halley Watch (IHW); the project's success resulted from extremely good international cooperation between the technical staff involved. The dual nature of the project (in which Intercosmos and NASA determined improved Vega trajectories using the NASA VLBI data, and Intercosmos and ESA determined an improved comet trajectory) required an intensive exchange of information, enabling a thorough preparation for the operations¹⁶⁻¹⁹, not least by facilitating communications between the groups with a newly established data link between Moscow and Darmstadt.

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First Halley Multicolour Camera imaging results from Giotto

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The first imaging results from the Halley Multicolour Camera (HMC) during the Giotto fly-by of comet Halley provide images centred on the brightest part of the inner coma which show the silhouette of a large, solid and irregularly shaped cometary nucleus and jet-like dust activity visible in reflected sunlight. A first assessment of the data yields information on the dimensions and shape of the nucleus and dust emission activity. The nucleus is at least 15 km long and ~10 km wide; its geometrical albedo is very low (<4%). Only minor parts of the surface are active, most of it being covered by non-volatile material. Dust jets dominate the inner coma and are restricted to the sub-solar hemisphere. Preliminary interpretations of these observations are presented. The parameters of the fly-by trajectory relative to the nucleus are given.

The first scientific objective of the HMC is to discover and observe the comet nucleus and to attempt to verify its solid nature and the general concept of the icy conglomerate model

of cometary nuclei, as proposed by Whipple¹ about 36 years ago. This objective involves the determination of the nucleus dimensions and shape, surface properties, photometric properties and spin-axis direction, as well as examination of mass loss and sublimation processes. The second objective is to gain insight into physical processes in the inner coma that are not accessible to ground-based observation. These processes include the interactive and spatial relationships between nucleus, gas and dust, the morphology of the dust jets and the characteristic scale lengths. In addition, the fly-by trajectory relative to the cometary nucleus can be determined using data obtained from the HMC. For this first assessment of results, only images taken through the clear filter ($\lambda = 300-1,000$ nm) are considered.

The telescope is a modified Ritchey-Chrétien design with correcting lens and a periscope mirror in front of the entrance pupil. It has a focal length of 998 mm and an effective speed of $f/7.7$. Data gathering is by line-scan imaging, making use of the image motion introduced by the spin of the spacecraft. Two charge-coupled devices (CCDs) with two sections each have been converted into four line sensors with analog storage areas by covering them with metal plates having narrow slits at the top of each section. When the image of the comet moves across a window, the charge packets on the CCD move at the same speed. Thus the instrument is operating effectively like a slit shutter camera, except that the slit is at rest and the image and 'film' (charge pattern) move together. The geometric resolution is $22.4 \times 22.4 \mu\text{rad}$ per pixel. A section corresponds to a field of view of $0.5 \times 0.36^\circ$. Three of the slit windows are exposed through fixed filters (red, blue and clear), and the fourth window through a filter wheel with 11 narrow-band, wide-band and polarizing filters. The exposure times range from 6 ms for a target near the spin axis to 57 μs for a target at 90° offset angle with respect to the spin axis, corresponding to closest approach to the comet. A dual-line diode array of width 1.6° is used to search for the comet at the beginning of the encounter operations.

The CCD signals are digitized to 12 bits with a gain switch for an additional factor of 4. The information is square-root-encoded, offering a dynamic range equivalent to a 14-bit word by transmitting only an 8-bit word to ground. Three microprocessors using 56 kbyte of software control the camera operations and performance such as computing the centroid of brightness of each image, predicting the offset angle and phase for the next exposure, and deducing the parameters of the fly-by trajectory.

Fig. 1 The inner dust coma of comet Halley with jets and the nucleus just resolved, seen from a distance of 124,050 km. The Sun is on the left, 7° below the horizontal and 17° behind the image plane. The frame size is 500 km. Isophotes at levels of $1/n$ of the maximum for $n = 2, 3, 4 \dots 10, 20, 30, 40$ are displayed so that equidistance verifies a drop-off with the inverse of the distance from the nucleus.

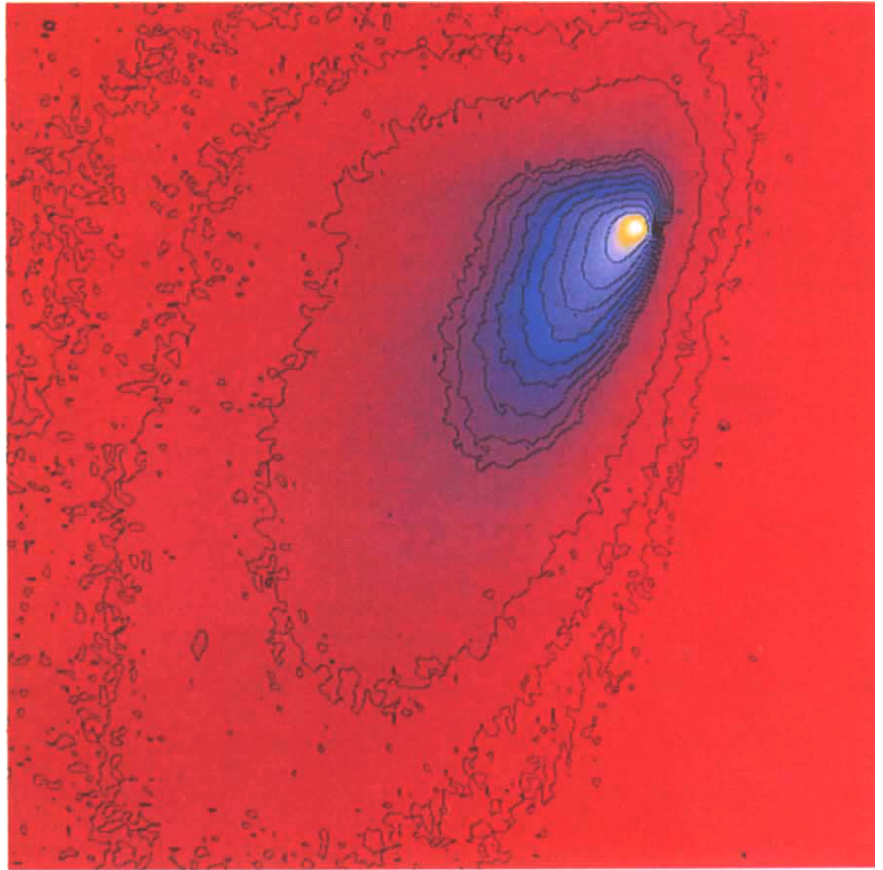
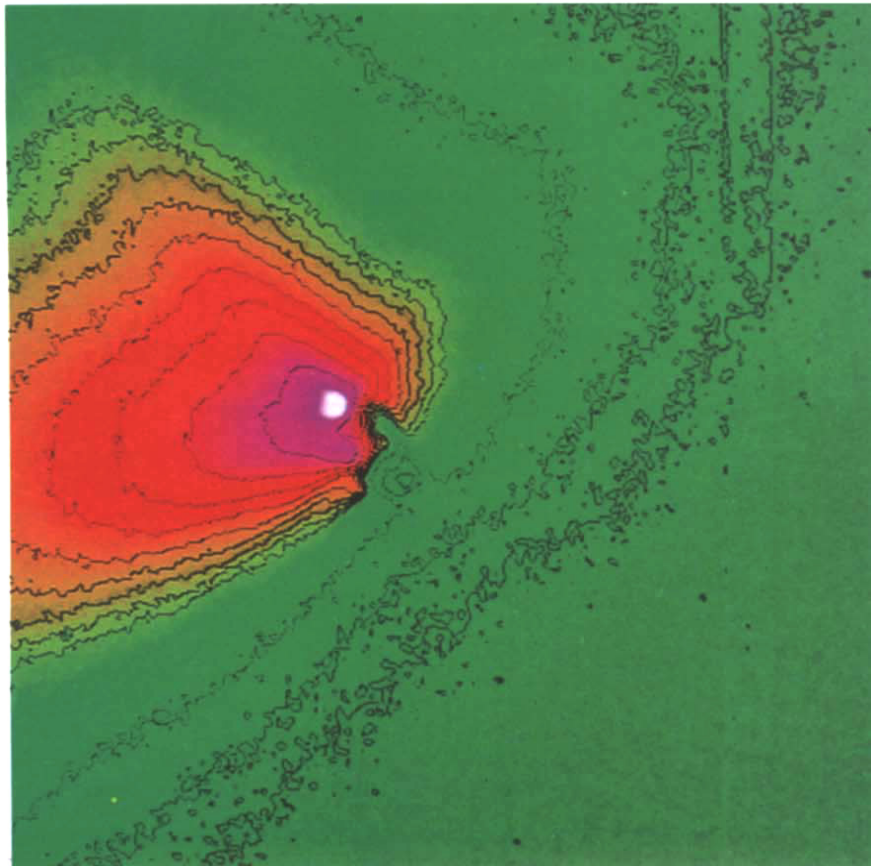


Fig. 2 The innermost coma with dust jets and nucleus seen from a distance of 25,650 km. The Sun is on the left, 26° above horizontal and 16° behind the image plane. Frame size 111 km. The isophotes have the same levels as for Fig. 1.



The camera was designed to search, acquire and track the comet automatically. The total mass of the camera and associated electronics is 13.5 kg, including 1.2 kg of balancing weights. Its power consumption is less than 12 W. (For more details see refs 2 and 3.)

The HMC was switched on for the final encounter operations at 19:43:15 UT on 13 March 1986. (All times given are spacecraft event times.) The acquisition procedure confirmed the direction to the comet as obtained in the morning of that day. The first comet image was taken at 20:55:00 UT. Because of the small angle of the relative velocity vector with respect to the spacecraft spin axis, the periscope mirror had to sweep the comet image across the central line sensor until the camera offset angle from the spacecraft axis reached 0.8° , after which the spin of the spacecraft could alone provide the sweeping. Altogether, 2,043 images were obtained in this 'single sensor mode'.

The 'multiple sensor mode' was automatically initiated at 23:58:07 UT when the offset angle became larger than 1.6° ; 70 image sequences from all four CCD sections were obtained with clear, blue and red filters with 2-pixel resolution, and with 1-pixel resolution with the clear filter. The last sequence of pictures of the comet was exposed at 1,703 km from the nucleus. An incomplete re-set command, probably originating from a glitch of the spacecraft power system (~ 12 s before closest approach) caused the camera to terminate the observations. The HMC radiator temperature increased by 12°C near the time of closest approach, indicating heat dissipation on the periscope mirror and radiator. Simultaneously, the spacecraft spin period increased from 3.998 s to 4.010 s. Dust impacts that caused sudden movements of the HMC periscope mirror and variations in the spacecraft attitude presumably were responsible for the observed behaviour. A complete re-set was required in order to reconfigure the instrument after closest approach. The comet could not be found, for reasons which are not yet fully understood.

The distance to the nucleus at closest approach, calculated from the camera offset angles, was 605 ± 8 km, which is in good agreement with the HMC real-time predictions. The direction of the vector from the comet to the spacecraft at closest approach was pointing $29.3 \pm 0.3^\circ$ south of the plane through the comet defined by the Sun-comet line and the velocity vector of the spacecraft relative to the comet. The time of closest approach, determined from the HMC data, was $00:03:02 \pm 1$ s UT on 14 March 1986. All distances and times presented here refer to these fly-by parameters.

The calibration of the camera was supported by in-flight observations of planetary and stellar objects. The overall camera alignment internal and relative to the spacecraft was found to be within 0.1° of the specifications. The images displayed have been preliminarily corrected for sensor background and variations in responsivity. We have not corrected for the slight geometrical distortions caused by the nonlinearity of the image motion.

Coma observations. The very short exposure times of HMC allow only observations of the brightest innermost part of the coma out to $\sim 2,000$ km. On a scale of 100–1,000 km, the HMC recorded a bright fan-shaped dust coma expanding from a bright spot into a sector extending over 70° from the sunward direction to the south. Weaker luminosity almost fills the sunward half space and extends slightly into the night side (Fig. 1). On still larger scales, beyond 1,000 km, our simultaneous observations from Earth, with a phase angle of 64° , show also a broad sunward fan consistent with the HMC image.

The isophotes of the fan-shaped coma in Figs 1 and 2 form nested polygons, with slightly protruding corners that are roughly self-similar and confocal. The fan appears to be composed of at least seven discrete jets that project onto respective corners of the nested isophotes, together with a diffuse background. The projections are largely in the sunward semicircle. The positions of these jets are indicated in Fig. 3, together with

estimates of their widths and brightness. Beyond a small distance from their apparent origin on the nucleus, all jets decrease in brightness proportional to the inverse distance. The projected centre lines of all jets intersect the brightest area in Fig. 2, which lies just on the sunward limb of the nucleus as proposed below. The dust activity on the nucleus (Fig. 4) does not always coincide with the jets observed at larger distances (Figs 1, 2). The projections of jets A and B point more than 90° away from the Sun, and the outermost isophotes, after crossing those two jets, engulf the cometary nucleus on the anti-sunward side.

Near to the nucleus the sunward brightness distribution is clearly dominated by discrete jets. Therefore, we consider it likely that jets A and B represent parts of a bundle of jets with an axis pointing very close to the line-of-sight away from the camera. We can assume that dust jets are accelerated by the evaporation of gas generally perpendicular to the sunlit surface on the nucleus and reach their terminal velocity of $\sim 0.5 \text{ km s}^{-1}$ within a few kilometres⁴. As the Sun is 17° behind our image plane, the bundle of jets near the line-of-sight probably has an inclination of less than 90° away from the Sun direction and its origin is located on a sunlit area in the northern hemisphere of the nucleus. As both jets point north of the spacecraft target point. If Figs 1 and 2 are compared, the isophotes connecting jets B and C are tilted clockwise by 8° relative to the comet-Sun direction. The projected angle between the two jets decreases, implying that, as both jets point jet B is substantially closer to the line-of-sight. Thus, most of the dust is probably expelled in jets from the sunlit surface into the sunward hemisphere. Active areas do not seem to exist during a cometary night. Smaller dust particles, however, are swept to the night side by the gas and produce the local foreground and background luminosity, which decreases towards the anti-solar dark area of the nucleus in Fig. 4. So far, we have found no time variation in the sources, nor effects due to rotation of the nucleus within the 3-h HMC observing window discussed here. For a rotation period of 52 h (refs 5, 6), these will be difficult to detect.

Because of the observed non-gravitational acceleration along the orbit, the rotation of the comet should be clockwise when viewed from the north¹. But existing estimates for the exact direction of the present spin axis are not consistent^{5,7}. One would expect the projected axis of maximum inertia of the comet to be normal to the long, almost straight limb on the night side of the nucleus as seen in Fig. 4, but this normal is inclined by 30° clockwise with respect to the projected spin axis of Sekanina and Larson⁵.

Nucleus observations. The nucleus is seen as a solid object of irregular shape visible as a dark silhouette against background light scattered by dust (Fig. 4). The edges of the nucleus on the night side are easily identified (outlined in Fig. 3). Part of the northern edge can be identified in the high-resolution images shown in Figs 5 and 6, for which the 1-pixel size corresponds to 110 m and 50 m, respectively. The largest dimension from the northern tip to the southern edge is 15 km, as projected on the sky. The sunward edge of the nucleus can hardly be seen through the dust jets. The largest width that can be clearly identified is ~ 7 km. Sources of strong jets near the northern tip are visible. Intensity traces along these jets show a gradual increase, rather than the sharp gradient expected and observed at places where the edge can be clearly identified. With the nucleus extending beyond these bright jets, a maximum width of the nucleus, projected on the sky, can be estimated to be ~ 10 km. This dimension will have to be substantiated by further image processing. From the best estimates of the silhouette of the nucleus and the approximated boundary under the jets, a projected area of $\sim 100 \text{ km}^2$ is obtained.

Almost no morphological features can be identified on the night side of the nucleus, except for a bright area near the 'waist', ~ 1.5 km in diameter, that can be interpreted as the sunlit side of a topographical relief with an elevation that extends into the sunlight. Preliminary processing of a number of images also

Fig. 3 Positions of jets found on Figs 1 and 2. All jets seem to originate from the sub-solar region of the nucleus, partly visible in the brightest spots of Figs 2, 4. The schematic diagram of the nucleus identifies some of its features and dust activity. The nearly straight edge (6 km long) on the night side shows structures that are several hundred metres in elevation and about 1 km long. The bright region in the centre (hatched area) is about 1.5 km in diameter. The visible part of the nucleus is indicated by a solid line, while the suspected edge under the jets is shown by a dotted line. — · — · — Indicates the minimum contour of the nucleus not hidden by dust.

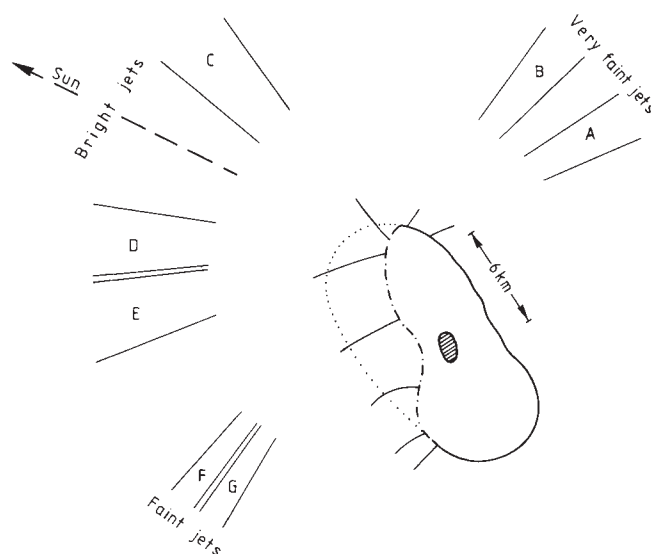


Fig. 4 The nucleus of comet Halley as seen from a distance of 18,270 km. The Sun is on the left, 27° above horizontal and 15° behind the image plane. The frame size is 30 km. Two bright jets appearing near the northern tip are directed towards the Sun. The bright region in the centre is probably a morphological feature protruding from the night side of the terminator that is struck by sunlight.



discloses a jet-like feature extending from the sunlit face of the nucleus towards the Sun. However, a detailed description of this feature will have to await full calibration of the images.

The roughness of the surface is particularly evident along the nearly straight edge on the night side and also from the diffuse but ragged appearance of the terminator and the abovementioned bright area in the middle of the nucleus. The brightness of the image changes by a factor of ~ 2 across the southern limb. There seems to be roughly as much dust in the column from the HMC to the nucleus as there is behind it. Some very dark patches in the anti-solar area are barely visible and cannot be readily interpreted; they may be artefacts of the data processing. The identification of the terminator is also not easy because its position depends on the shape of the nucleus, the roughness of

the terrain, and contamination by light scattered from the jets and the dusty environment. Furthermore, the illuminated portion of the nucleus is visible only in small regions not hidden by the dust jets.

Figure 3 also indicates preliminary estimates of the roughness of the nearly straight edge on the night side, obtained using several images. The maximum slope of local features seen in profile is $\sim 15^\circ$, suggesting a rough 'crater-type' terrain. The various types of observed features are typically in the kilometre range, well resolvable with the optical system used. As the ground resolution during fly-by varies from 450 m per pixel at a distance of $\sim 20,000$ km to 45 m per pixel at a distance of $\sim 2,000$ km, morphological features of the order of less than 1 km can be identified. Consequently, both the ragged appear-

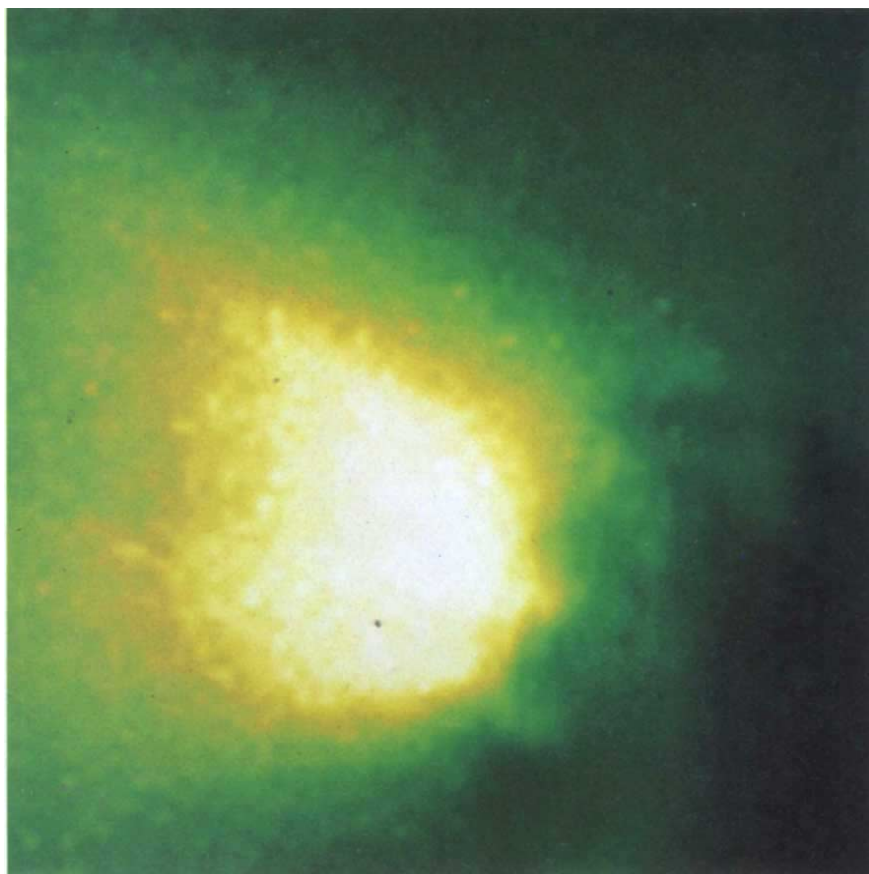


Fig. 5 The source of the bright dust jet on the northern tip of the nucleus as seen from a distance of 4,910 km. The Sun is on the left, 30° above horizontal and 11° behind the image plane. Frame size 8 km. The active area is ~ 3 km in diameter. Morphological features with dimensions of a few hundred metres are apparent. The scalloped areas in the source region are ~ 0.5 km across and appear to be the sources of smaller jets that combine to form the large jet.

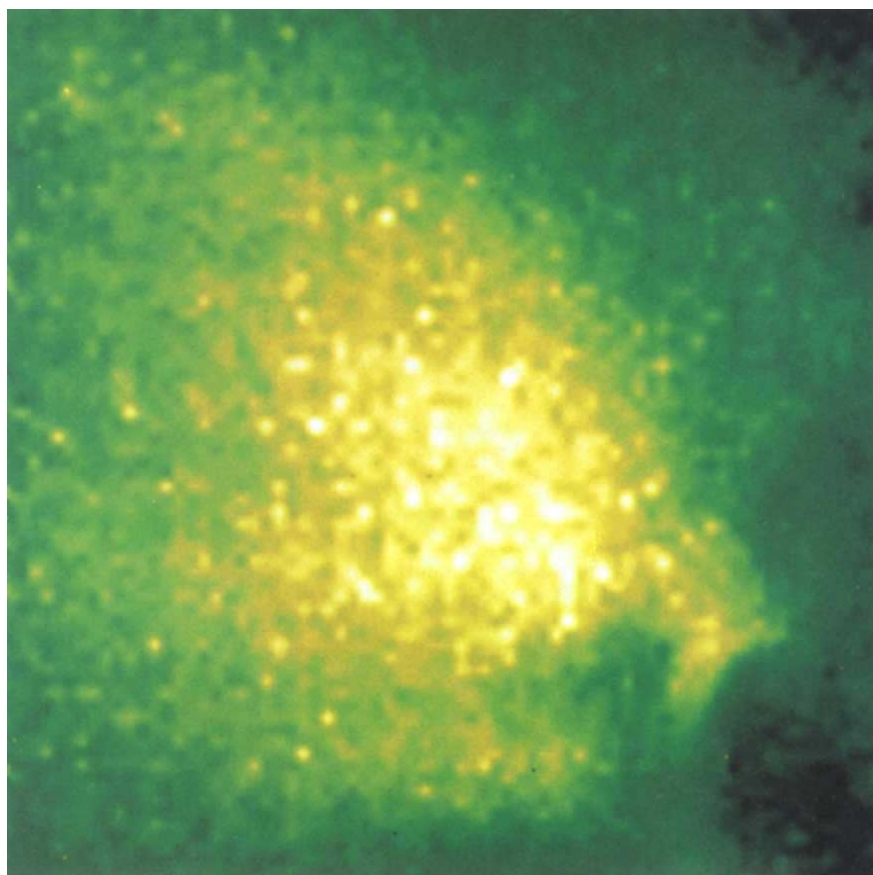


Fig. 6 Details of a jet source in high resolution, as seen from 2,220 km. The Sun is on the left, 29° above the horizontal and 4° behind the image plane. Frame size 3.7 km. This is one of the last images taken by the HMC.

ance of the terminator and the scalloped morphology in the sunlit active areas are attributed to the presence of features in the hundred-metre range.

The area in which the large bundle of jets has its origin near the northern tip of the nucleus shows scalloped features resembling craters (Fig. 5), each of which appears to be the source of a narrow jet. A series of light and dark patches can be interpreted as undulating morphological features or craters with dimensions of half a kilometre. The diameter of the source region for the jet bundles is ~ 3 km. Figure 6 shows one of the last images received from the camera that shows identifiable features on the nucleus. Further details will have to await extensive image processing and the use of images in the other colour bands.

Visual photometry of a comet at a large distance from the Sun can be used to measure the product $p_v S$, where p_v is the visual geometric albedo⁸ and S is the effective cross-section of the nucleus, provided one assumes that the bare nucleus is actually observed without dust activity. Unfortunately, it is usually not possible to separate the two quantities p_v and S . Here, for the first time, the direct observation of the size of the nucleus of comet Halley allows this separation.

For comet Halley, at large solar distance, when inactive, Hughes⁹ found

$$p_v = (1.2/R)^2$$

where R is the effective radius, in kilometres, of an equivalent spherical nucleus. Sekanina¹⁰ determined the average value for the numerical constant to be 1.1 km. Our value of $S = (100 \text{ km}^2)$ corresponds to $R = 5.6$ km, yielding $p_v = 0.04$. For comparison, C-type asteroids have an albedo of ~ 0.04 (ref. 11) and p_v for the moon is 0.11 (ref. 8), indicating that the comet's nucleus at full phase has about one-third the reflectivity of the moon.

On the other hand, if the large and irregular brightness variations reported by Sekanina were caused by some dust activity, as assumed for the comet Halley reference model¹², then the geometric albedo at full phase would turn out to be lower than 0.02. It is clear, however, that the nucleus is not spherical and the HMC pictures only show it in projection. The brightness variations quoted by Sekanina are thus to some extent caused by variations of the observed cross-section and possibly the albedo as the nucleus rotates. Hence, the typical value of p_v is probably near the lower limit quoted above.

Preliminary interpretation of the signal from the brightest part of the northern jet bundle (Fig. 4) indicates that the dust is optically thin ($\tau < 0.1$), assuming a rather low particle albedo (including phase dependence) of $A_p = 0.03$ (ref. 12). The poor visibility of the illuminated parts of the nucleus can then be explained only by a low (< 0.5) 'effective' albedo, in our case reflectivity, of the nucleus, defined as the ratio of the surface to dust reflectivity¹³. If all the brightness is attributed to the illuminated surface, a coarse upper limit of < 0.02 is found for its reflectivity, including the phase (107°) effect towards the observer. All this leads to the surface being virtually invisible if viewed through larger amounts of dust, as for instance from the sub-solar side.

The separation of the two large jets near the base on the sunlit side of the nucleus is ~ 5.5 km in projection, while the diameters of the envelopes at the points of inflection of their maximum intensity profiles are ~ 3 km. The line representing the maximum intensity along the northern of the two jets, when projected back, points almost exactly to the northern tip of the nucleus. Small curvatures of the jets near the nucleus are possibly caused by superposition of intensity profiles from other jets.

Conclusions. For the first time it has been possible to detect the nucleus of a comet unambiguously. The 'heart' of comet Halley was clearly visible on the images of HMC once the distance to the comet became less than 70,000 km, $\sim 1,000$ s before closest approach. The apparent size of $\sim 15 \text{ km} \times 7\text{--}10 \text{ km}$ is larger than had been widely anticipated. Direct measurement of the surface

reflectivity on the sunlit portions of the nucleus is difficult because of the presence of dust near the active regions. However, combining the early observations of the comet's magnitude with the presently determined cross-section of the nucleus yields values for the albedo in the lowest range of any known object in the Solar System. The large nuclear cross-section, together with an albedo < 1 , leads to strong solar energy absorption on the surface. If the ice were not protected by an insulating crust on the surface, then the total gas and dust production would be about an order of magnitude higher than observed. Therefore, one can conclude that most of the surface of the nucleus of comet Halley has to be covered by a non-volatile, insulating crust of dark material. The very low albedo values could be caused by a small-scale roughness or porosity of the surface trapping the light in tiny cavities (fluffy dust particles). A similarly low albedo is found in the case of C- and D-type asteroids¹⁴. Indeed, old, 'burnt-out' cometary nuclei may very well look like such asteroids.

The HMC images show in addition that the sublimation process is strongly concentrated on the sunlit side of the nucleus and that the strong activity is restricted to relatively small areas, typically of kilometre size. If each of the seven identified jets has a source area equal to that of the largest jets, namely $7 \times 10^{10} \text{ cm}^2$, the total active area amounts to $\sim 5 \times 10^{11} \text{ cm}^2$; this is $\sim 10\%$ of the surface area of the observed nucleus or equivalent to a sphere of only 2 km radius that uniformly produces dust. With a nominal production rate of $5 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}$ (assuming water ice and a low albedo), the total gas production would be $3 \times 10^{29} \text{ s}^{-1}$, which is almost consistent with the OH production rate of $5 \times 10^{29} \text{ s}^{-1}$ estimated from IUE (International Ultraviolet Explorer) observations (M. Festou, personal communication). However, should measurements made by other instruments during closest approach show a higher gas production rate, then there must be either (1) more jets than have been identified, (2) general outgassing without production of visible dust grains, (3) gas production in the jets from materials more volatile than water, or (4) jets with ice-covered grains that produce additional gas as the ice sublimates from the grains.

The dust-generating sources produce bundles of small, strongly collimated jets which cross one another when seen in projection on the sky. At close range, roughly circular structures are seen on the surface and jets appear to emanate from this rough terrain. Variations in elevation of several hundred metres over distances of a few kilometres are revealed on the night-side edge.

The thickness of the crust has to be large enough to insulate the ice within the nucleus from solar heat. Therefore, the temperature of most of the surface is not controlled directly by sublimation. There is no evidence of a more or less uniform, dust-producing activity over large parts of the surface. Dust particles seem to be swept towards the night side in the vicinity of the surface. Dust-free sublimation of water cannot be detected by the HMC. However, many observations from the ground and in particular by IUE (M. Festou, personal communication) show also a pronounced asymmetry of the gas component, including daughter species such as OH. This requires the predominant outflow velocity of the mother molecules, such as water, to be towards the Sun.

Models describing the nucleus as uniform are seen to be inadequate. The small total area of active regions requires large fluxes of gas and dust release; here the temperature will be considerably lower and controlled by the sublimation process. As no bright spots (with albedo > 0.1) have been detected so far, we must assume that the ice is 'dirty' even in the active centres. The irregular shape of the nucleus indicates that the ice does not sublimate uniformly from beneath the crust on a long timescale; this suggests that the structure of the nucleus is not homogeneous. More volatile parts could be interdispersed, possibly in reservoirs, with less volatile materials including clumps and aggregates of refractory material. If evaporation of the ice

continues into the evening, recondensation and freezing may occur in the crust, giving rise to subsequent cracking under thermal stresses. The crust should have a variable thickness reflecting the non-uniformity of the sublimation and the roughness of the terrain.

It is difficult to imagine a shape of the nucleus that would result in a moment of inertia consistent with the proposed direction(s) of the spin axis.

In summary, the nucleus of comet Halley does not look like a simple 'dirty snowball'. It is irregular in shape and has a rough, dark exterior covered with a non-volatile crust that must become much hotter than the equilibrium temperature of sublimating water ice. The volume and mass of the nucleus seem to be an order of magnitude larger than anticipated. Outgassing and dust emission are strongly anisotropic, being concentrated in small areas on the sunlit hemisphere.

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In situ gas and ion measurements at comet Halley

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The neutral mass spectrometer experiment (NMS) carried by the Giotto spacecraft was designed to determine the abundances and the chemical, elemental and isotopic composition of the gases and low-energy ions in the coma of comet Halley. Its first results show the predominance of water vapour (~80% by volume). Preliminary evaluation of the data yields an H₂O density of 4.7×10^7 molecules cm⁻³ at 1,000 km, a neutral gas expansion velocity of 0.9 km s⁻¹ and a total gas production rate of 6.9×10^{29} molecules s⁻¹. The photodestruction scale length for H₂O was 3.9×10^4 km. Limits on the abundances of CO₂, NH₃ and CH₄ relative to H₂O are given. The contact surface was located at $4,700 \pm 200$ km, as observed from a change in ion temperature. The water-group ions H₃O⁺, H₂O⁺ and OH⁺ have been unambiguously identified, along with the ions ¹²C⁺, ¹²CH⁺, ¹⁶O⁺, Na⁺, ¹²C₂⁺, ³²S⁺, ³⁴S⁺ and ⁵⁶Fe⁺. The ³⁴S⁺/³²S⁺ ratio is 0.045 ± 0.010 . General features of the low-energy ion flow at large distances from the nucleus are presented.

The neutral gas spectrometer (NMS) on the Giotto spacecraft provided *in situ* measurements of the composition of gases and

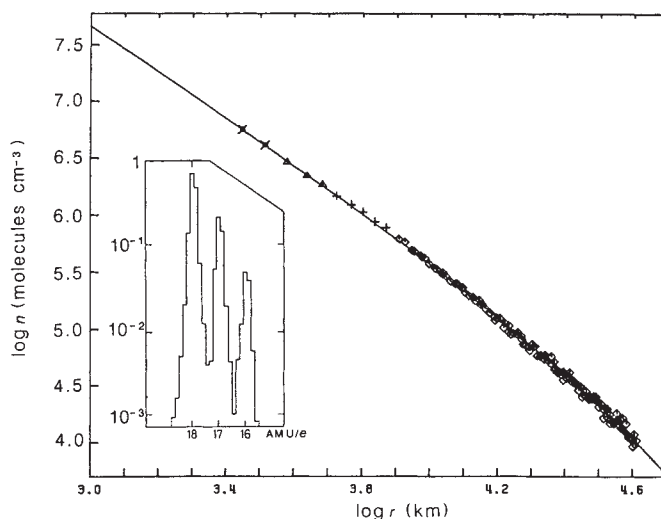


Fig. 1 Water-vapour number density (n) derived from M-analyser data, plotted against distance from the nucleus (r). The figure shows all gain-step data recorded from 00:01:02 to 00:10:29 UT on 14 March at 90 eV ionization. The curve represents a photodestruction model with constant expansion velocity [$n(r) = c_0 r^{-2} \exp(-c_1 r)$]. The constants $c_0 = (4.72 \pm 0.17) \times 10^{13}$ molecules cm⁻³ km² and $c_1 = (-2.51 \pm 0.13) \times 10^{-5}$ km⁻¹ were obtained by a least-squares fit to all data at the highest detector gain (diamonds; 2σ errors). The data obtained in lower gains (different symbol used for each step) were normalized to this best-fit line, because the absolute calibration data for these gain steps were not yet available. The slope defined by these latter data points matches exactly the slope of the curve. The inset shows the mass range 16-18 AMU/e of the neutral mass spectrum recorded at a distance of 2,280 km.

ions in the coma of comet Halley. The NMS consisted of two analysers: a double-focusing mass spectrometer (M-analyser) and an electrostatic energy spectrometer (E-analyser). The M-analyser covered the mass range from 1 to 37 AMU/e. In the gas mode the E-analyser covered energies from 200 to 2,150 eV (in three ranges); in the ion mode from 20 to 1,420 eV (in two

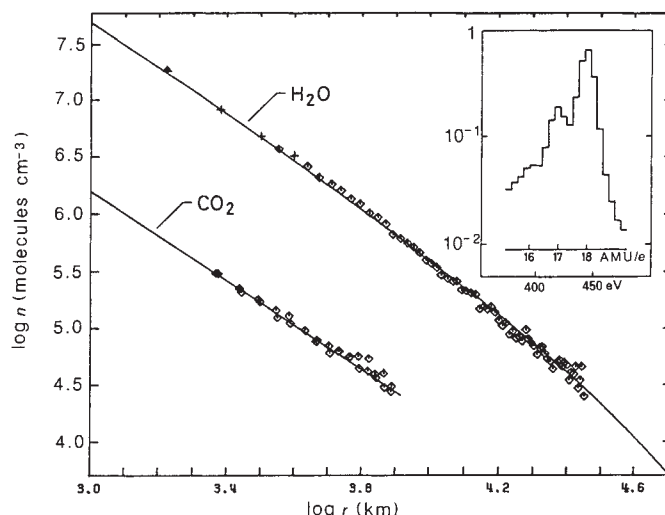


Fig. 2 Water vapour (H_2O) and carbon dioxide (CO_2) number densities derived from E-analyser data, plotted against distance from the nucleus. For H_2O all measurements at 90 eV ionization from 00:04:05 to 00:10:38 UT are shown. Symbols represent different detector gain steps to which the relative gain factors known from detector calibration were applied. One existing measurement from <1,000 km is not shown because a steep increase of background requires further analysis for appropriate correction. The curve represents the same model as in Fig. 1, with constants $c_0 = (5.08 \pm 0.31) \times 10^{13} \text{ molecules cm}^{-3} \text{ km}^2$ and $c_1 = (-2.67 \pm 0.35) \times 10^{-5} \text{ km}^{-1}$. The CO_2 number density is derived assuming that the mass 44 peak includes no contribution from other species. The curve is a fit to the data points which emphasizes data obtained between 2,300 and 4,000 km. The inset shows the energy range equivalent to masses 16–18 from a neutral energy spectrum recorded at 3,180 km.

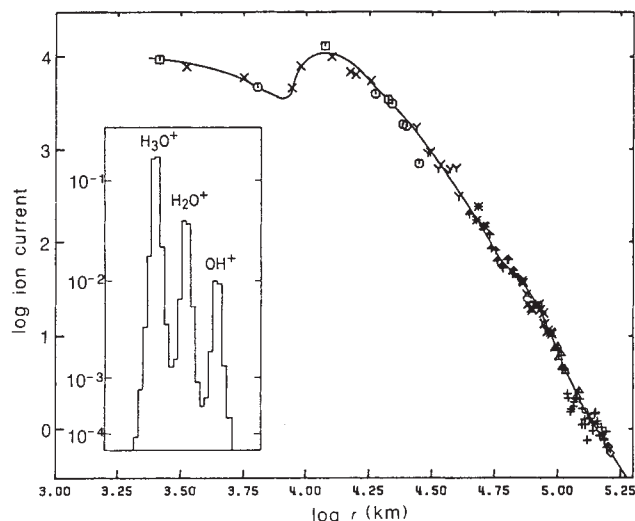


Fig. 3 Total ion current recorded in the 12–37 AMU/e mass range of the M-analyser, plotted against distance from the nucleus. Different symbols refer to different gain steps. Data obtained in the high-gain and toggled modes are not shown. The inset shows the 17–19 AMU/e mass range of an ion spectrum recorded at a distance of 2,570 km.

ranges). For thermal cometary particles this corresponds to mass ranges 8–86 AMU/e for the neutral gas and 1–56 AMU/e for ions. Both analysers used electron bombardment ion sources with either 90-eV or 17-eV electrons for ionizing the neutral gas, and cometary ions were suppressed by electrostatic deflection plates and a potential barrier while operating in the neutral mode.

Focal-plane detectors covered the whole mass range of the M-analyser and the selected energy range of the E-analyser. The

detectors comprised microchannel plate (MCP) electron multipliers operated as analog preamplifiers, followed by linear arrays of sequentially scanned charge collectors. The M-detector had 256 individual pixels, the E-detector 128 pixels. The detector sensitivity could be changed by adjusting the MCP high voltage to 16 predetermined steps, resulting in a range of full-scale sensitivities covering more than 7 decades. The appropriate gain step for each analyser and each mode was determined by an automatic gain control algorithm in a microprocessor. The inherent dynamic range was $\sim 1:10,000$ for a fixed gain step. Periodically, the gain was increased by a factor of 30 in a high-gain mode, in which dominant peaks saturated while minor peaks were enhanced. The entire mass spectrum of the M-analyser was periodically shifted (toggled) by $\sim 1.5 \text{ AMU/e}$ to aid in resolving peaks that normally fell near the junction of two MCPs.

The NMS operated in one of two sequences. In the neutral-ion sequence (NIS), 10 neutral and 4 ion spectra were recorded in each format (22.67 s), along with measurements of the background from neutral-neutral collisions. In the steered ion sequence (SIS), the analysers were operated in ion mode only. The electrostatic deflection plates were used to scan the view axis of both analysers simultaneously through a conical region with 30° half-angle centred on the spacecraft spin axis. After 15 formats with different combinations of deflection angles, a total of 17 formats in NIS were recorded as part of the SIS sequence. For a more detailed description of the NMS and its operating modes the reader is referred to ref. 1.

All results in this paper are based on the on-line data provided during encounter. Times are reported as UT at the ground receiving station; spacecraft UT can be obtained by subtracting the 480.1 s propagation time. We assume that the closest approach occurred on 14 March 1986, at 00:11:00.5 UT, that the miss-distance was 600 km and the spacecraft velocity relative to the comet was 68.373 km s^{-1} .

The NMS was switched into the SIS sequence at 20:26:03 UT on 13 March, when the distance to the comet was 922,900 km. At a distance of 352,500 km the instrument was commanded into the NIS sequence. Useful data were obtained from both analysers until 00:10:51 UT on 14 March, at an estimated distance of 880 km from the nucleus. At this time all detector pixels in both analysers failed, probably due to a large-amplitude electrical transient.

The instrument performed as expected, with a few irregularities appearing in the data suggesting dust impacts within an analyser inlet or on the spacecraft dust shield. The only significant anomalous event was the failure of two of the 128 detector pixels on the E-analyser at 00:00:08 UT. Unfortunately, the lost pixels were numbers 84 and 85, on which ions with a mass-to-charge ratio of 44 AMU/e were focused in the ion mode.

Gas measurements. The neutral gas composition of the coma is clearly dominated by water and other light constituents with molecular masses (strictly, M/Q) up to 44 AMU/e . In the NMS data the first evidence of neutral gas is the appearance of water vapour, the OH radical and atomic oxygen at $\sim 150,000 \text{ km}$. Water remains the main gaseous constituent throughout the encounter. With decreasing distance from the comet, other neutral species appear in the data. From 11,000 km inward, each integer mass position of the M-analyser spectrum from 12 to 37 AMU/e has a well-defined peak. The E-analyser, with its extended mass range of up to 86 AMU/e , detected several species above mass 37.

H_2O density. Figures 1 and 2 show preliminary radial profiles of water vapour density from the M- and E-analysers, respectively. These data sets were reduced independently to demonstrate consistency. H_2O number densities were obtained from the raw data by taking into account: (1) the MCP gain factors for each pixel; (2) the measured background from neutral-neutral collisions; (3) the absolute sensitivities of the instrument as determined from laboratory calibrations with neutral beams

of N_2 and Ne at 69 km s^{-1} velocity; and (4) cross-section and yield differences between N_2 , Ne and H_2O .

The two independently measured water vapour profiles agree rather well. The ordinate scales may be altered by future refinement of in-flight detector calibration schemes, but the nature of the radial variation of the measured H_2O profiles is unlikely to change. The curves that overlay the data points represent 'least-square-error' fits to the data of a photodissociation model with constant radial expansion velocity. At 1,000 km from the nucleus, the extrapolated H_2O densities are 4.6×10^7 and $4.9 \times 10^7 \text{ molecules cm}^{-3}$ for the M- and E-analyser, respectively. We estimate the error, mainly due to the preliminary nature of the data reduction, to be $\pm 40\%$. The photodestruction scale lengths for the two data sets are $(3.98 \pm 0.21) \times 10^4$ and $(3.75 \pm 0.50) \times 10^4 \text{ km}$, respectively (2σ errors).

Bulk motion and H_2O production rate. Information on the gas flow can be obtained independently from the position of the peaks of identified masses in the E-analyser. The expected peak-shift from the expansion velocity of 1 km s^{-1} is only 13 eV for mass 18, and a very careful data reduction and comparison with calibration data is necessary. The available results indicate an expansion velocity of $(900 \pm 200) \text{ m s}^{-1}$ at distances closer than 10,000 km.

The measured neutral H_2O density and velocity correspond to an H_2O production rate of $5.5 \times 10^{29} \text{ molecules s}^{-1}$ ($\sim 1.5 \times 10^7 \text{ g s}^{-1}$), with an uncertainty estimated as $\pm 50\%$. The photodestruction scale length of $3.9 \times 10^4 \text{ km}$ and the 900 m s^{-1} expansion velocity give a photodestruction lifetime of $4.3 \times 10^4 \text{ s}$. This is considerably shorter than the generally accepted photodestruction time of $6.6 \times 10^4 \text{ s}$ (from ref. 2, recalculated for 0.89 AU). This is not surprising, as the solar ultraviolet flux shows large variations⁴.

Composition. Figure 2 also shows the radial dependence of the mass 44 peak in the E-analyser. Several different molecules (CO_2 , C_3H_8 , CS, ethylene oxide and acetaldehyde) could contribute to this peak. From the abundance of fragment peaks we conclude that C_3H_8 , ethylene oxide and acetaldehyde together cannot contribute more than one third of the measured peak intensity at mass 44. Disregarding at present this possible contribution, as well as any possible contribution from CS, we obtain a CO_2/H_2O volume mixing ratio of 3.5%. The data imply a CO_2 gas production rate of $1.9 \times 10^{28} \text{ molecules s}^{-1}$. The upper limit on the NH_3 volume mixing ratio (relative to H_2O) is 10% and the upper limit on CH_4 is 7%.

By comparing the magnitude of the major neutral mass spectrum peaks measured by the M-analyser, and taking CO_2 into account, we conclude that water vapour accounts for $>80\%$ by volume of the gases escaping from the comet. The total gas production rate then amounts to $6.9 \times 10^{29} \text{ molecules s}^{-1}$, with an uncertainty of $\pm 50\%$.

Ion measurements. Immediately after switch-on the M-analyser recorded a well-resolved proton peak. The first O^+ ions were detected at a distance of $\sim 550,000 \text{ km}$ from the nucleus, and at 400,000 and 350,000 km, respectively, well-resolved peaks at 12 and 17 AMU/e appeared, representing $^{12}C^+$ and OH^+ .

The M-analyser is double-focusing and, in principle, does not give information on the energy of the ions. However, the energy focusing range of the M-analyser is limited to approximately ± 5 to $\pm 10 \text{ eV}$ in the cometary reference frame (corresponding to plus-or-minus several hundred eV in the instrument reference frame, depending on mass). If ions have a larger energy spread the peak begins to widen and develops a tail. In the outer coma, the interaction with the solar wind leads to a rapid acceleration of newly formed ions. In the M-analyser the well-resolved mass peak represents this newly formed ion population, whereas the more energetic ions contribute to the observed broad tails. Evidence for energetic ions persisted until $\sim 40,000 \text{ km}$ from the nucleus. Often large fluctuations are apparent between spectra recorded 6 s apart, indicating spatial structure with scale lengths of $\leq 400 \text{ km}$. It is important to note that the M-analyser measures

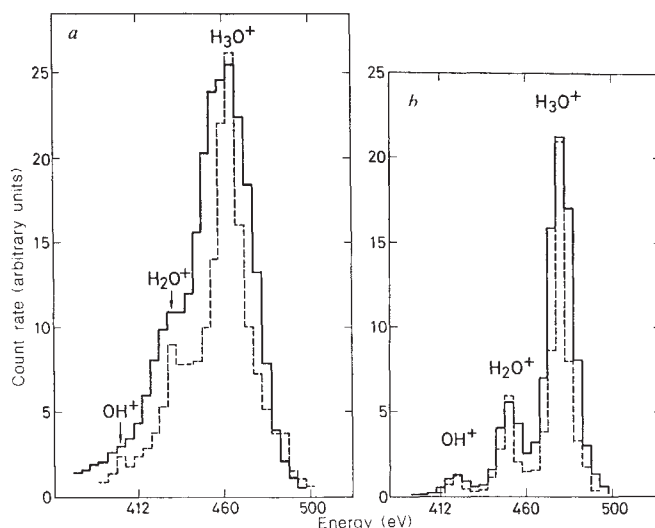


Fig. 4 Two energy spectra (solid lines) of ion species of mass 17–19 AMU/e, measured outside (a) and inside (b) the contact surface (a: 14 March, 00:09:49 UT, $r = 4,930 \text{ km}$; b: 14 March, 00:10:01 UT, $r = 4,140 \text{ km}$). Theoretical simulation results (dotted lines) based on the assumption of a Maxwellian particle distribution with temperatures of 10,000 K (a) and 1,300 K (b) are shown for comparison, demonstrating the dramatic change which occurs in the ion temperature on crossing the contact surface. Because analyser and detector aberrations already account for a basic peak width similar to that observed in b, only an upper limit can be placed on the ion temperature inside the contact surface.

all masses simultaneously. The integration period in the ion mode is 0.75 s, and read-out of the pixels from mass 37 to 1 AMU/e takes 63 ms. Each spectrum thus represents the true average ion population on a 51-km trajectory segment, with an offset of only 4.3 km from the high- to the low-mass end.

The E-analyser (which, unlike the M-analyser, is not energy focusing) translates energies of a few eV in the cometary reference frame into much larger energies observed on the instrument scale, due to the superposition of the ram velocity. At distances greater than 28,000 km, the E-analyser data indicate the presence of several ion species with energies (in the instrument frame of reference) spread over a few hundred eV, obscuring features identifiable with specific ion species. At $\sim 28,000 \text{ km}$ the energy spread decreases sharply and three distinct but broad peaks appear at positions in the spectrum where thermal cometary ions with approximate masses of 18, 32 and 44 would be located. At $\sim 4,700 \pm 200 \text{ km}$ the spacecraft crossed the contact surface, where a second change in the nature of the ion energy spectrum occurred. Inside the contact surface the E-analyser resolved thermal cometary ion peaks. Above 37 AMU/e (top of M-analyser mass range), peaks were detected at almost all integer mass numbers up to mass 56.

Outer coma. The orientation of the instrument in the spacecraft and the limited phase-space acceptance function of the analysers prevented the detection of the highly collimated solar-wind ions before the solar wind had been considerably slowed down and thermalized by cometary interactions. However, ions formed in the outer coma by ionization of cometary gases could be measured. Such ions initially perform a cycloidal motion perpendicular to the local magnetic field orientation. The amplitude and direction of their velocity are modulated at the gyro-frequency and thus fall periodically within the energy and angular acceptance range of the instrument in the SIS sequence. Scattering by intrinsic fluctuations of the interplanetary magnetic field or by instabilities resulting from the ion angular distribution itself alter the angular distribution, which becomes more isotropic.

Quantitative analysis of the SIS data obtained between 922,900 and 352,500 km requires a precise knowledge of the interplanetary magnetic field in this region; however, some of the observed general trends in the data have obvious implications. At the beginning of the SIS measurements, ions detected by the instrument came predominantly from a direction northward of the ecliptic plane, with a very small angular spread in arrival directions. This implies a large solar-wind flow velocity and a weak pitch-angle diffusion. The observed northward bias of ion arrival directions, perpendicular to the ecliptic plane, must be due to the particular geometry of the magnetic field. At $\sim 500,000$ km the observed angular distribution of arrival directions became more nearly isotropic, indicating a significant reduction of the solar-wind velocity and stronger pitch-angle diffusion. However, the north-south bias of the flow remained. **Total ion density.** Figure 3 shows the total ion current recorded by the M-analyser in the mass range 12–37 AMU/e. For a thermal plasma with temperature $T < 10,000$ K the instrument inlet acceptance function is essentially independent of both temperature and mass. This condition holds within the contact surface and probably outside to a distance of $\sim 15,000$ km. In this region the total ion current shown is directly proportional to the total ion density. The steep decrease in ion current at distances greater than 15,000 km is probably due to the limited phase-space acceptance function of the instrument.

The ion concentration profile has a minimum near 8,000 km and increases by a factor of 3 at 12,000 km. A similar feature should result from increasing electron temperature with increasing distance, which would cause the rate of dissociative recombination of molecular ions, mainly H_3O^+ and H_2O^+ , to decrease. However, the measured effect is much larger than predicted by Marconi and Mendis³, and the radial increase in ion concentration occurred far from the contact surface where the maximum gradient of electron temperature is expected. Thus, it seems more likely that the increase in ion concentration was due to enhanced ionization, possibly from an increasing flux of energetic electrons or from the appearance of a minor neutral species with a very high photoionization cross-section, or to particular transport conditions (for example, flux piling). The full explanation of this feature awaits the completion of the data analysis, in particular the determination of the chemical composition of the ions and neutrals.

Contact surface. Between 4,900 and 4,500 km from the nucleus the nature of the ion energy spectrum recorded by the E-analyser indicated a sudden fall in ion temperature as the spacecraft crossed the contact surface. Figure 4 illustrates the significant differences between the energy distributions of the water-group ions outside (Fig. 4a) and inside (Fig. 4b) the contact surface. A preliminary analysis indicates that the ion temperature outside the contact surface is $> 7,000$ K and inside it is $< 1,500$ K. From the common energy shift of all ion species we estimate that the spacecraft potential changed from $\sim +16$ V outside the contact surface to ~ 0 V inside.

Ion composition. The mass resolution of the M-analyser in the ion mode throughout the mass range 12–37 AMU/e was similar to the example shown in the Fig. 3 inset; thus, mass assignments to all observed mass peaks are completely unambiguous. Closer to the nucleus, well-resolved mass peaks are present at all integer mass positions from 12 to 37, except for mass 22. For many mass positions the identification of the ion species is ambiguous and requires a detailed analysis of the data as well as ion-

chemical model calculations; however, for some ions a firm identification can already be made:

H_3O^+ , H_2O^+ , OH^+ . Close to the comet the water-group ions are dominant (see Fig. 3 inset). The $\text{H}_3\text{O}^+/\text{H}_2\text{O}^+$ ratio increases with decreasing distance and exceeds unity at distances of $\leq 20,000$ km. Mass 17 may be a mixture of OH^+ and NH_3^+ ions. The $17^+/\text{H}_2\text{O}^+$ ratio increases from 0.4 close to the nucleus to unity at 50,000 km, probably reflecting a relative increase in the OH^+ density.

$^{12}\text{C}^+$. The M-analyser recorded a well-resolved mass peak at 12 AMU/e at a distance of 400,000 km from the nucleus. From the shape of the mass peak it is evident that these $^{12}\text{C}^+$ ions have a suprathermal component and an energy spectrum that changes rapidly with distance. The radial density profile of the $^{12}\text{C}^+$ ions is typical for a daughter product.

$^{12}\text{CH}^+$. Ions at mass position 13 were seen in all ion spectra from distances $< 50,000$ km. From the variation of the observed $13^+/12^+$ ratio with distance it is concluded that the peak at mass 13 is a mixture of $^{12}\text{CH}^+$ and $^{13}\text{C}^+$.

O^+ . At distances of $\leq 550,000$ km the M-analyser detected ions at mass 16, which we identify as O^+ . Molecular ions which could also contribute to this mass position are destroyed by photodissociation before they reach such large distances. From the observed peak shape we conclude that these O^+ ions have a suprathermal component and an energy distribution changing on a distance scale of $< 10,000$ km. Closer to the nucleus, CH_4^+ and NH_2^+ ions probably contribute to the mass 16 peak.

Na^+ . At distances greater than 5,000 km, essentially no ions are detected at 23 AMU/e. The Na^+ abundance at these distances is less than 2×10^{-5} of the total ion number density. Closer to the nucleus Na^+ ions are clearly present, with a relative abundance increasing with decreasing distance.

$^{12}\text{C}_2^+$. Ions at mass position 24 are present in all spectra recorded closer than 50,000 km. As no Na^+ ions are present at such distances we identify these ions as $^{12}\text{C}_2^+$ and not $^{24}\text{Mg}^+$.

S^+ . A well-resolved peak at mass position 32 was evident in all ion spectra at distances $< 290,000$ km from the nucleus. This ion is one of the major ions, and in some spectra it is dominant. A preliminary evaluation indicates that the $34^+/32^+$ abundance ratio close to the nucleus is 0.045 ± 0.010 , which agrees with the terrestrial $^{34}\text{S}/^{32}\text{S}$ ratio of 0.044. It is concluded that the ion at mass 32 is S^+ and that the cometary isotopic ratio $^{34}\text{S}/^{32}\text{S}$ is identical to the terrestrial ratio within $\pm 25\%$.

Fe^+ . Inside the contact surface, mass 56 was detected in the E-analyser spectra and is tentatively identified as Fe^+ .

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Ion composition and dynamics at comet Halley

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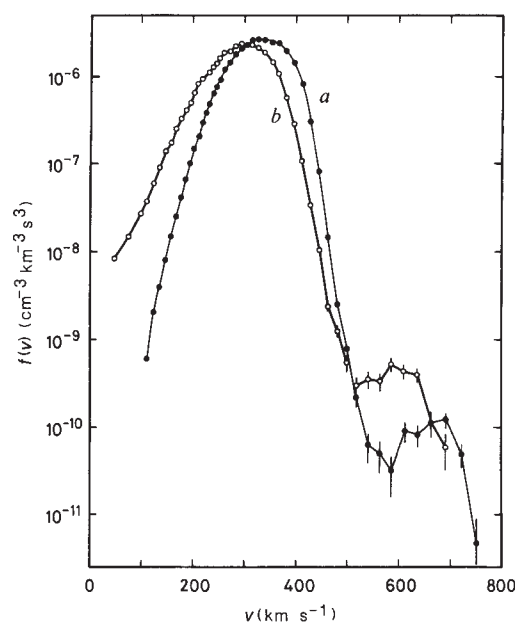


Fig. 1 The distributions of proton velocities parallel to the solar-wind velocity vector for two intervals before Giotto crossed the cometary bow shock. *a*: 13 March, 14:49–15:42 UT; proton speed, proton density and thermal Mach number: 334 km s^{-1} , 5 cm^{-3} , 5.5. *b*: 13 March, 19:03–19:27; solar wind parameters: 284 km s^{-1} , 6 cm^{-3} , 4.3. The thermal Mach number is defined as v/w , where v is the solar-wind velocity and the thermal speed $w = (2kT/M)^{1/2}$, where M is the proton mass.

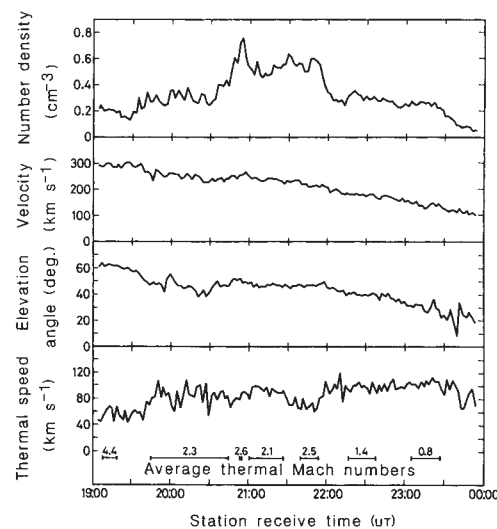


Fig. 2 Plasma parameters for the $M/Q=2$ ions, based on moments calculated from preliminary data. All plotted parameters are relative to the spacecraft reference frame, whereas the spacecraft velocity has been removed for calculation of the average thermal Mach numbers given below the plotted data. The elevation angle is measured from the spacecraft velocity vector; the solar direction has an elevation angle of 72.5° .

The ion mass spectrometer aboard the Giotto spacecraft measured the composition and velocity distributions of cometary ions at distances of $\sim 7.5 \times 10^6$ to $\sim 1,300 \text{ km}$ from the nucleus of comet Halley. Well outside the bow shock, pick-up cometary H^+ ions were found in a diffuse shell-like distribution. Heavier ions (C^+ , H_2O^+ -group, CO^+ and S^+) with similar distributions have been identified at $\leq 3 \times 10^5 \text{ km}$. Solar-wind He^{2+} was found throughout the coma to as close as $\sim 5,000 \text{ km}$; He^+ produced by charge exchange was seen inside $\sim 2 \times 10^5 \text{ km}$. Deeper within the coma the main cometary hot-ion species identified were H^+ , H_2^+ , C^+ , O^+ , OH^+ , H_2O^+ , H_3O^+ , CO^+ and S^+ . A pile-up of heavy cometary ions was found at $\sim 10^4 \text{ km}$ from the nucleus. Giotto crossed the contact surface at $\sim 4,600 \text{ km}$, based on changes in ion flow velocity and temperature. Inside, ion temperatures as low as $\sim 340 \text{ K}$ and outflow velocities of $\sim 1 \text{ km s}^{-1}$ were found. Outside the contact surface ion densities vary as r^{-2} , with a transition to an r^{-1} dependence approximately at the contact surface. A large C^+ abundance throughout the coma indicates an unexpected direct source of atomic carbon. The nitrogen abundance, on the other hand, is relatively low.

The Giotto ion mass spectrometer (IMS) consists of two independent sensors: the high-energy-range spectrometer (HERS), which is optimized primarily for the study of ion abundances and velocity distributions outside the contact surface (CS); and the high-intensity spectrometer (HIS), which provides similar information primarily inside the CS. Both sensors returned complementary data of excellent quality throughout the encounter to within a few seconds of closest approach (CA), after which only the HIS returned data. We have reported elsewhere on the optical principles of the IMS and on its flight configuration and initial in-flight calibration¹. The HERS and the HIS are true mass spectrometers using variable electric fields and static magnetic fields for simultaneous determination of energy per charge (E/Q), mass per charge (M/Q) and velocity distributions. The HERS E/Q range is 10 to $4,500 \text{ eV/e}$, depending on mass and including typical solar-wind energies. The HIS range is 300 to $1,400 \text{ eV/e}$. Both instrument fields of view are fans which rotate with the spinning spacecraft. Fan angles (called elevation angles) relative to the spin axis are $+15^\circ$ to $+75^\circ$ for the HERS (thus excluding the ram direction but including the solar-wind direction) and -3° to $+12^\circ$ for the HIS. Times to collect a full mass spectrum, including angular and energy information, are 16 s and 4 s for HERS and HIS, respectively.

Although calibration and background factors have been applied where indicated, the data must still be considered in some sense preliminary. A common system of coordinates and nomenclature has not yet been established by the Giotto

experimenters, so here we refer to ground-station received time (in UT) and convert this to distance from the nucleus based on CA = 605 km on 14 March, 00:11:00 UT.

Plasma dynamics of solar-wind interaction. Pick-up protons of cometary origin first became noticeable in 53-min averages of the HERS proton-mode data at $\sim 18:00 \text{ UT}$ on 12 March ($\sim 7.5 \times 10^6 \text{ km}$ from the nucleus). Figure 1 shows two proton velocity spectra measured on 13 March in a 22° (azimuth) by 15° (elevation) angular sector which included the direction to the Sun.

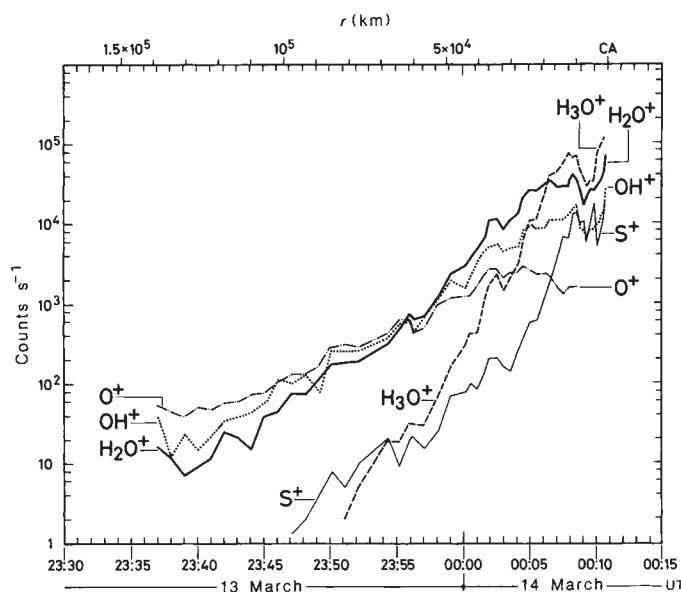


Fig. 3 Time profiles of the HIS count rates for masses 16, 17, 18 and 19 as well as the mass 32-34 group. Time is ground-station received time in UT; r , distance of Giotto from the nucleus.

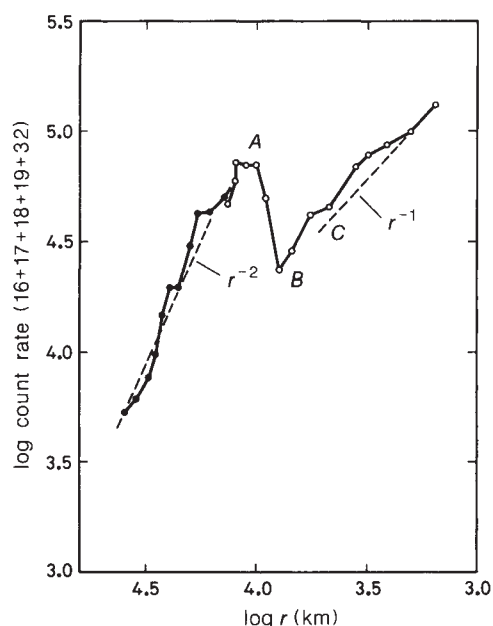


Fig. 4 Radial profile of the sum of the HIS count rates for masses 16, 17, 18, 19 and 32, showing that inside the 'contact surface' (C, at $r \approx 4,600$ km) the total count rate tends to follow an r^{-1} dependence and that in the outer part ($r > 16,000$ km) an r^{-2} dependence fits the data quite well. Open circles, H-mode data; dots, N-mode data (see ref. 1).

Spectrum *a* was obtained at a distance of $\sim 2.2 \times 10^6$ km, and spectrum *b* at a distance of $\sim 1.2 \times 10^6$ km during the half-hour preceding the bow-shock crossing. Both spectra show secondary peaks at twice the solar-wind speed. This spectral shape is quite different from the power-law spectrum derived for water-group ions picked up near comet Giacobini-Zinner². Examination of three-dimensional data obtained over the $360^\circ \times 60^\circ$ field of view of the HERS instrument reveals that these picked-up protons were distributed over a spherical shell in phase space; this shell was centred on the solar-wind bulk velocity and had a radius equal to the solar-wind speed. Such a distribution function is

consistent with rapid pitch-angle scattering of newly ionized hydrogen out of the expected initial cycloidal trajectories.

The features of spectra *a* and *b* listed in Fig. 1 legend illustrate that as Giotto approached the comet, the solar wind became slower, denser and hotter, as expected from models of the mass loading of the solar wind by photoionization of cometary gases³⁻⁵. As the mass loading proceeded, the relative number of protons in the shell increased from 0.2% of all protons in spectrum *a* to 0.7% in spectrum *b*. Clearly, most of the deceleration must have been caused by the pick-up of ions heavier than protons (see ref. 6, which describes the results of the implanted ion sensor).

The ions detected by HERS at $M/Q = 2$ AMU/e provide a good tracer for plasma variations associated with the comet-solar wind interaction because that M/Q value is expected to be populated primarily by solar-wind alpha particles until very close to the comet where cometary H_2^+ becomes an important constituent. Preliminary estimates of plasma parameters were obtained by taking moments of the $M/Q = 2$ distributions after subtracting the estimated background count rates. No adjustments were made for the part of the particle beam outside the HERS field of view; such corrections can be substantial when the beam is incident at elevation angles near 15° or 75° .

Figure 2 shows 128-s averages of the resulting parameters as measured in the spacecraft frame of reference, as functions of time. A weak but definite bow-shock-like transition was observed shortly after 19:30 UT at $\sim 1.15 \times 10^6$ km from the nucleus. The bulk speed decreased, number density and thermal speed increased, and the flow angle changed by $\sim 10^\circ$, rotating away from the Sun-comet line. The average thermal Mach number dropped from 4.4 before to 2.3 after the shock. The protons underwent equivalent changes, and the highest-time-resolution proton data (1 spectrum every 16 s) suggest multiple crossings of the shock between 19:30 and 19:39 UT. The identification of a bow shock close to the theoretically expected location is one clear difference from the plasma observations at comet Giacobini-Zinner⁷.

After the shock, there is a roughly steady decrease in speed and in apparent elevation angle. When the effect of the spacecraft velocity is removed, it is seen that the plasma speed decreased rather steadily from ~ 300 to < 100 km s⁻¹ between 19:40 UT (1.1×10^6 km) and 23:40 UT (1.2×10^5 km), while the flow direction fluctuated between 20° and 40° away from the Sun-comet line. The density and thermal speed (and the thermal Mach number) showed a more structured radial profile through this region. From $\sim 20:45$ to $21:55$ UT the density was greater by a factor of ~ 2 , while the flow direction shifted back to a more nearly anti-sunward direction. During the same period the magnetometer observed a considerably quieter field than during the preceding hour⁸. This high-density structure may have been caused by temporal variation in either the solar wind or the gas emitted from the comet.

Following the region of high density, the speed continued to decrease, causing the apparent flow direction to turn more towards the ram direction. After $\sim 22:00$ UT, the $M/Q = 2$ ions developed a very non-thermal distribution, suggestive of the presence of H_2^+ ions in addition to He^{2+} (see below), and by the end of the day, 25-50% of the $M/Q = 2$ ions had dropped out of the HERS field of view. At 23:40 UT there was a very large fluctuation in the plasma flow direction.

Plasma dynamics of coma ions. Between $\sim 22:00$ and $\sim 23:53$ UT (5.4×10^5 to 7.4×10^4 km), HERS detected an increasing flux of hot cometary ions; the mass spectra of these ions are described below. Then, beginning at $\sim 23:53$ UT, the ion fluxes seen by HERS decreased while the HIS ion count rates increased. Figure 3 shows HIS count rate profiles for several ion species. By $\sim 00:05:30$ (22,500 km), the ion population was so stagnant and cold that the HERS count rates were down to background levels (except for the protons, which decreased in count rate, but did not disappear). We attribute this strong cooling of the solar-

wind ion component to charge exchange and collisional effects. The distribution of cometary ions in this collision-dominated region was, however, still significantly affected by the solar-wind flow; this is demonstrated by the steeper than r^{-1} dependence of the HIS count rates at radial distances $>10^4$ km. In Fig. 4 we show that an r^{-2} dependence fits the data quite well. At point C (Figs 4 and 5), 4,600 km from the nucleus, we identify a clear discontinuity in ion velocity and temperature, which we call the 'contact surface' (see Fig. 5). At the same location the magnetic field strength dropped to zero⁸. The r^{-1} dependence of the count rate inside such a diamagnetic cavity has been predicted by photochemical equilibrium models in which the photoionization of cometary neutrals is balanced by electron dissociative recombination in a spherically symmetric coma.

One of the distinct features of the ion profile is the apparent pile-up of heavy ions just outside 10^4 km from the nucleus (A in Fig. 4) and the subsequent minimum (B). The discontinuity in the count rates between A and B is not yet well understood. Several effects could be involved here. First, the coma outside the contact surface confining the ionospheric outflow may be permeated by a flux of ionizing electrons: these electrons would not only produce additional ions but due to their much higher temperature the electron recombination loss would be reduced, thus producing enhanced ion concentration. Second, the possibility of plasma transport along the draped field lines in the 'magnetosheath' could produce the minimum in region B (ref. 4). Finally, the observed structure may be simply temporal, reflecting a change in the solar-wind condition and/or in the outgassing of the comet.

A major function of the HIS instrument was to measure the velocity distribution function for different ion species in the cometary ionosphere. Fig. 5 shows the time profiles of the flow speeds determined from the mass 18 (H_2O^+) and 19 (H_3O^+) ions (after subtraction of the spacecraft speed), as well as the corresponding temperatures (T_i). Although further analysis will be required to clarify the several fine-scale structures, the general trend of larger flow speeds and temperatures at larger distances from the cometary nucleus is obvious. Also, the drastic change in ion temperature at $\sim 00:09:54$ UT, from 2,600 to ≤ 450 K, is quite striking. The drop in temperature coincides with a sudden onset of a $\sim 1 \text{ km s}^{-1}$ flow velocity outwards from the comet. As mentioned, we call this discontinuity the 'contact surface'. The measured outflow speed for the ionospheric plasma is in general agreement with theoretical calculations; the low temperature of the water-group ions inside the contact surface can be understood in terms of a balance between photolytic heating of the expanding ionospheric plasma and the very efficient cooling effect of collisions with H_2O molecules⁹.

Ion composition from HERS mass spectra. Figure 6 shows relative M/Q count-rate spectra acquired in three radial intervals, indicated in the legend. Examination of the three-dimensional velocity distributions of all of the prominent ion constituents observed in the medium (M-mode; $M/Q = 12-26$) and heavy (H-mode; $M/Q = 15-34$) mass modes showed that they were very nearly identical. The spectra shown are averaged over the full width at half-maximum of these distributions.

The M/Q peaks shown in Fig. 6 are derived from laboratory calibrations; the identification of specific ion species associated with the M/Q measurements is discussed below. The transformation from ion count rate to density is dependent on mass, energy and elevation angle, but to a rough approximation the count rates are proportional to phase-space density divided by $(M/Q)^4$. This relationship has been confirmed by performing the detailed transformation for a limited number of cases and the results are shown in Table 1.

Figure 7 shows light-ion (L-mode) spectra recorded at two radial distances. Figure 7a, from $2.5-3.2 \times 10^5$ km, is characteristic for a region inside the bow wave which is still dominated by solar-wind ions. Mass peaks are shown for He^{2+} , O^{7+} , O^{6+} and C^{5+} , which are typically identified in solar-wind spectra¹⁰.

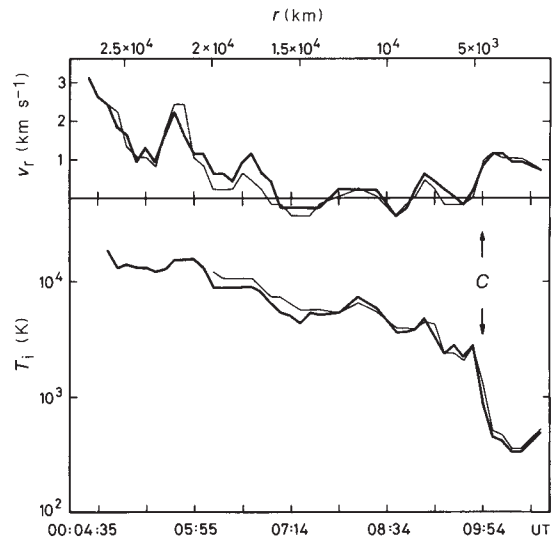


Fig. 5 Time profiles of the ionospheric flow speed relative to the comet (v_i) and temperature (T_i) derived from an analysis of the HIS count rates of mass 18 (H_2O^+ ; bold line) and 19 (H_3O^+ ; thin line). Note that v_i changes from near-zero to $\sim 1 \text{ km s}^{-1}$ at the contact surface (C). At the same location, T_i decreases rapidly from 2,600 to ≤ 450 K.

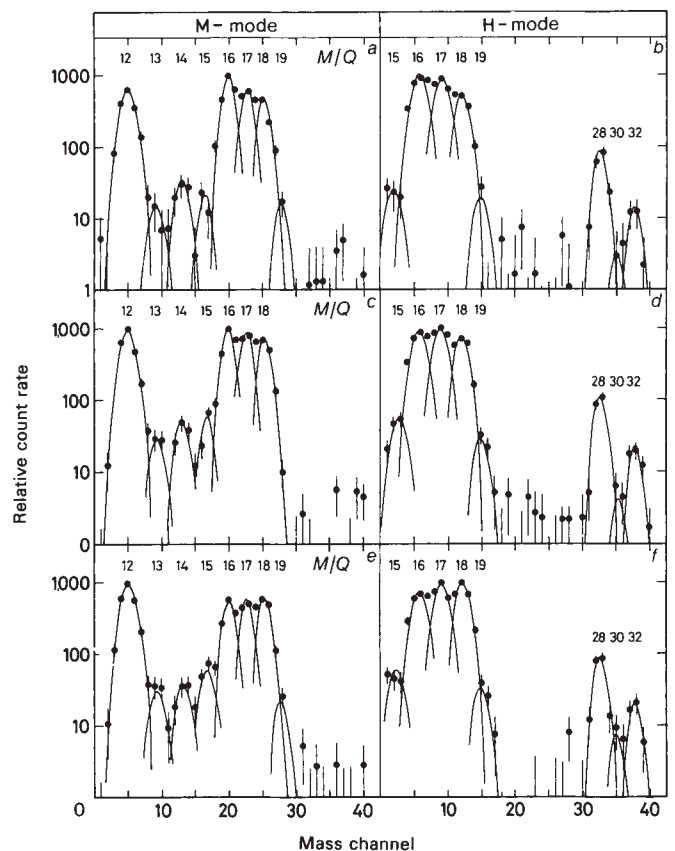


Fig. 6 M/Q spectra acquired by HERS in three radial intervals. a, b: 13 March, 23:25-23:44 UT; $r = 1.1-1.7 \times 10^5$ km. c, d: 13 March, 23:54 UT; $r = 0.7-1.1 \times 10^5$ km. e, f: 13/14 March, 23:53-00:02 UT; $r = 3.5-7.0 \times 10^4$ km. Error bars indicate one standard deviation based on counting statistics only. To a rough approximation, count rates are proportional to relative phase-space densities divided by $(M/Q)^4$. M/Q peaks are shown to indicate the response to specific mass components.

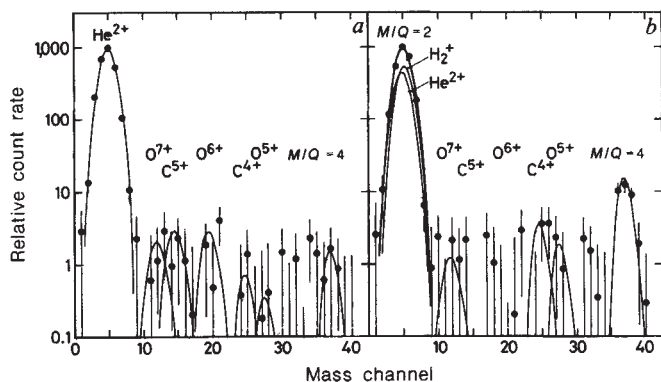


Fig. 7 Light-ion mass spectra from HERS in, *a*, the outer coma (13 March, 22:54-23:10 UT; $r = 2.5\text{--}3.2 \times 10^5$ km), indicating primarily unaltered solar-wind composition and, *b*, deeper in the coma (13/14 March, 23:44-00:03 UT, $r = 0.3\text{--}1.1 \times 10^5$ km), showing a mixture of partially charge-exchanged solar-wind ions (in particular He^+) and cometary hydrogen, H_2^+ .

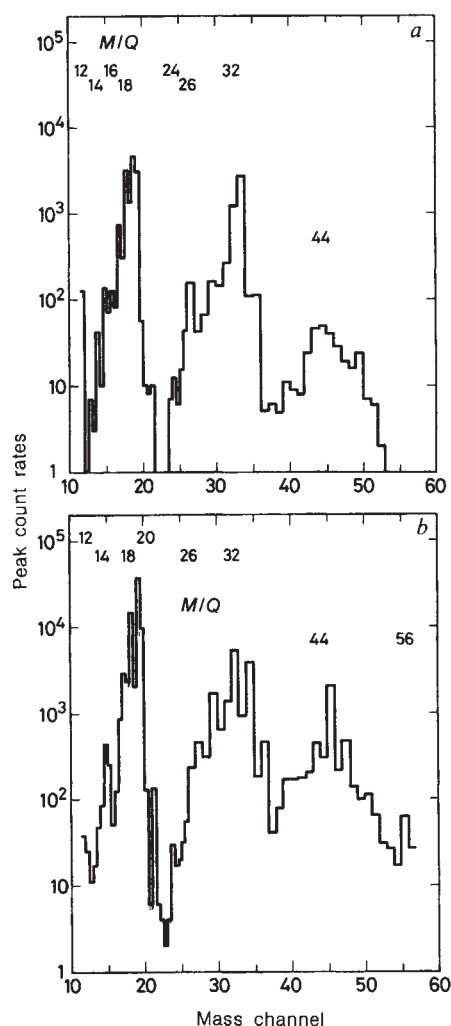


Fig. 8 Peak count rates from HIS in H-mode (see ref. 1) obtained in one spin. *a*: 14 March, 00:09:32 UT; $r = 6,000$ km (outside the contact surface). *b*: 14 March, 00:10:42; $r = 1,500$ km (inside the contact surface). Note that mass channels are not identical with M/Q .

There is some evidence for peaks at $M/Q = 3$ (C^{4+}), 3.2 (O^{5+}) and 4. These latter appear more clearly in the inner region (Fig. 7*b*, from $0.3\text{--}1.1 \times 10^5$ km), which is dominated by cometary ions (see Fig. 6*c-f*) and charge-exchanged solar-wind ions. Here we identify a major contribution of cometary H_2^+ to the $M/Q = 2$ peak. From the $M/Q = 4$ peak we infer that $\sim 30\%$ of solar-wind helium has charge-exchanged to He^+ . The $M/Q = 3$ peak could contain cometary H_3^+ in addition to the solar-wind C^{4+} .

After count rates in HERS had dropped to background level (by $\sim 00:05:30$ UT), a flux of hot ions abruptly reappeared approximately at or inside the contact surface ($\sim 4,600$ km). The last data transmission received from HERS (00:10:36 UT) indicated instantaneous H-mode ($M/Q = 15\text{--}34$) count rates higher than at any other time during the inbound pass of Giotto. The ions showed quite low bulk speed (equal to or less than the ram velocity), with a thermal distribution corresponding to a Mach number of ~ 1 . They were of mainly cometary origin, quite similar to the composition observed by HERS further out. The $M/Q = 2$ peak was identified as mainly cometary H_2^+ . More extensive analysis, including the investigation of possible influence from dust impact and spacecraft charging shortly before closest approach, will be required to understand these data in more detail.

Ion composition from HIS mass spectra. HIS observed ion spectra from $\sim 2 \times 10^5$ km through closest approach. It was operated in two different modes, called N and H (ref. 1). Figure 8 shows two spectra from the H-mode. More detailed analysis and inclusion of both modes will eventually lead to relative ion densities and spectra better resolved than those shown here. Nonetheless, a number of important observations regarding species identification can be readily made. There are three prominent groups of ions seen in Fig. 8. The most abundant is the water group at $M/Q = 17\text{--}19$. The pattern exhibited by the ion group $M/Q = 13\text{--}16$ is characteristic of methane, with some contribution at $M/Q = 16$ from O^+ . Although the instrument sensitivity is significantly reduced at $M/Q = 12$, a relatively large peak is observed from C^+ . The second group of ions at $M/Q = 24\text{--}34$ is the region in which CO^+ , HCN^+ , H_2S^+ , C_2H_n^+ hydrocarbons, single-carbon organics and sulphur contribute. This second group is dominated at distances $> 4,000$ km by the S^+ ion ($M/Q = 32$). The third group of ions at $M/Q = 36\text{--}54$ is the region in which CO_2^+ , the C_3H_n^+ and C_4H_n^+ hydrocarbons, other two- and three-carbon organics and sulphur species such as CS^+ and SO^+ contribute. Chemical modelling will be required to provide specific identifications in the second and third groups.

A comparison of the two mass spectra (Fig. 8*a, b*), one taken at 6,000 km and the other at 1,500 km, indicates substantial changes in ion composition as a function of the radial distance. The increase in the count rates of species other than the H_2O^+ , CO^+ , S^+ and CO_2^+ group ions at smaller distances to the nucleus is particularly noteworthy; this suggests a significant contribution of hydrocarbons and carbon organics to the ion chemistry in the inner coma.

More thorough analysis of the innermost spectra should also lead to the resolution of the $M/Q = 20$ ($\text{H}_2\text{D}^{16}\text{O}^+ + \text{H}_3^{17}\text{O}^+ + \text{H}_2^{18}\text{O}^+$) and 21 (mainly $\text{H}_3^{18}\text{O}^+$) peaks from the main water-group peaks 17 ($^{16}\text{OH}^+$), 18 (mainly $\text{H}_2^{16}\text{O}^+$) and 19 (mainly $\text{H}_3^{16}\text{O}^+$) and thus give us the opportunity to deduce the D/H ratio in cometary water.

Ion chemistry. Outside the contact surface, at distances from the nucleus of $0.35\text{--}1.7 \times 10^5$ km, the most abundant ions are O^+ at $M/Q = 16$, OH^+ at $M/Q = 17$, and H_2O^+ at $M/Q = 18$. The relative count rates at $M/Q = 16\text{--}18$ versus cometary distance (see Fig. 3) are consistent with the successive photodissociation of water to OH and O followed by photoionization of each component. There is some contribution at $M/Q = 17$ from dissociative photoionization of H_2O to OH^+ . At these distances from the nucleus, ion-molecule reactions in the coma are not important and the count rate at $M/Q = 19$ (H_3O^+) is low.

The C^+ ion at $M/Q = 12$ has an unexpectedly high abundance. The intensity at $M/Q = 13$ is too large for this ion to be due to the ^{13}C isotope alone: the main contributor to $M/Q = 13$ is the CH^+ ion. Assuming that CH^+ , CH_2^+ and CH_3^+ are the major contributors to $M/Q = 13$ –15, and considering the respective photodissociation and ionization rates, a mixture of 2–7% methane in water fits the ion intensity distribution fairly well, including the variation with radial distance out to $\sim 10^5$ km. At greater distances there may be a contribution at $M/Q = 14$ from N^+ ions. At this early stage in the data analysis, we find no definite evidence for the presence of NH_3 in the ion mass spectra.

In the outer coma the major ions in the spectrum beyond $M/Q = 19$ are CO^+ at $H/Q = 28$, S^+ at $M/Q = 32$ and CO_2^+ at $M/Q = 44$. The ion at $M/Q = 28$ is most likely the CO^+ ion rather than N_2^+ . An upper limit for the contribution of the N_2^+ ion to $M/Q = 28$ can be deduced by using the $M/Q = 14$ peak in the HERS spectrum at 1.1 – 1.7×10^5 km (Fig. 6a, b) to derive the required $M/Q = 28$ intensity. In this particular spectrum, N_2^+ can contribute no more than 10% to the total $M/Q = 28$ intensity.

The S^+ ions arise from the photoionization of S atoms, which are in turn the result of the photodissociation of CS , S_2 , CS_2 , H_2S and other sulphur-containing species. The ultraviolet emissions of the first two species have been seen in several comets by the International Ultraviolet Explorer spacecraft^{11,12}. The relative count rates of the S^+ ions and the H_2O -group ions suggests that the production rate of the sulphur-containing parent molecules is $\sim 10^{-3}$ times that of the water molecules. The S^+ count rate, however, increases to $\sim 10\%$ that of the H_3O^+ ions at $\sim 1,500$ km (Fig. 8b). This enhancement can be explained by the shorter photoionization timescale and much longer electron radiative recombination time for S^+ ions as compared with water ions¹³.

In view of the possible identification of Na^+ and/or Mg^+ ions in the ion tail of comet Giacobini-Zinner¹⁴, a surprise in the Halley encounter observations is the near-absence of Na^+ ions (Fig. 8). The peak at $M/Q = 56$ in Fig. 8b persists in several measurements and may possibly be the Fe^+ ion.

Inside $\sim 2 \times 10^4$ km, the dominance of H_3O^+ demonstrates the importance of ion-molecule reactions. The dominance of H_3O^+ also requires that the abundance of NH_3 be less than $\sim 3\%$ that of H_2O ^{13,15}. The peaks at $M/Q = 28$ and 29 which would be expected from CO^+ and HCO^+ are less significant inside the contact surface because of the high reactivity of these ions towards H_2O . The same holds true for CO_2^+ and HCO_2^+ ions at $M/Q = 44$ and 45. The relative intensities of ions with $M/Q = 28$ and 44 outside the contact surface indicate that there is somewhat less CO_2^+ than CO^+ . There are also significant numbers of ions present in the spectrum at $M/Q = 24$ –27, where C_2H_2 and HCN contribute.

A major surprise in the HERS data is the very large signal from the C^+ ion at $M/Q = 12$. Dissociative photoionization of

CO , CH_4 and CO_2 , and photodissociation of CO , CH_4 and CO_2 to C followed by photoionization of C , together cannot account for all of the C^+ ions in the HERS mass spectrum. The simplest explanation is that the $M/Q = 12$ peak arises from atomic carbon. If expressed as atomic carbon, this component of the cometary gas would be 5–10% of the total number of oxygen atoms at these distances. HIS, although providing only a lower limit for C^+ , also indicates a large abundance of C^+ at all distances. Either there is an additional, hitherto unexpected ionization mechanism leading selectively to C^+ , or there is an unexpected source of atomic carbon in the coma of comet Halley. Carbon atoms might be released directly at the surface, or the source may be the dust grains themselves. Carbonaceous grains in the coma may be stimulated by solar ultraviolet photons to release carbon in atomic form, or as a highly unsaturated compound. Small carbonaceous dust grains as observed by the Giotto particle impact analyser¹⁶ will have a high temperature in the coma¹⁷ and slow outgassing could provide a distributed source of some material readily photolysed to atomic carbon.

While the IMS spectra show a striking richness in carbon they also show a noticeable lack of nitrogen. Using the HERS ion densities from Table 1 at the range 0.70 – 1.1×10^5 km, we find a bulk C/O ratio of 0.33, an upper limit to the N/O ratio of ≤ 0.01 and an S/O ratio of 0.03. The C/O ratio is about half the cosmic ratio, the N/O ratio is low by an order of magnitude, and the S/O ratio is cosmic.

Table 1 HERS preliminary ion number densities (cm^{-3})

Range ($\times 10^5$ km)	$M/Q = 12$	16	17	18	28	32
0.35–0.70	3.4	5.6	8.6	11	6.1	
0.70–1.1	5.3	16	18	18	14	5.9
1.1–1.7	2.6	11	8.8	6.9	6.2	

The rather high abundance for CO that would be derived from the ratio of $M/Q = 28$ to water-group ion densities in Table 1 ($CO/H_2O \approx 0.2$) is only an upper limit because this CO represents all carbonaceous gas-phase species processed by photochemistry in the coma to CO .

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Mass spectra of heavy ions near comet Halley

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The heavy-ion analyser, RPA2-PICCA, aboard the Giotto spacecraft, detected the first cometary ions at a distance of $\sim 1.05 \times 10^6$ km from the nucleus of comet Halley. In the inner coma the major ions identified are associated with the H_2O , CO and CO_2 groups. Ions of larger atomic mass unit are also present, corresponding possibly to various hydrocarbons, heavy metals of the iron-group or to sulphur compounds.

Spectral observations of comets from the ground as well as from Earth-orbiting satellites have revealed a variety of neutral and ionic species. However, reliable cometocentric radial profiles of the number densities of individual species, which are required for comparison with atmospheric/ionospheric cometary models, have not been available.

The RPA2-PICCA (positive ion cluster composition analyser) experiment, which is part of the RPA-Copernic plasma instrument (ref. 1 and A.K. *et al.*, in preparation), is designed to measure ion densities in the mass range from 10 to 213 AMU along the flight path of the Giotto spacecraft. The PICCA sensor consists of a deflection unit followed by an electrostatic analyser. To determine the mass, we make use of the large relative fly-by velocity and of the fact that the ions in the inner coma should have low temperatures and should be predominantly singly charged. Thus, the E/Q (energy/charge) measurements can be directly related to the mass distribution of the ions by $E(\text{eV}) \approx 5.1 \times 10^{-3} M \nu^2$, where M is the ion mass in AMU and ν is the relative velocity of 68.4 km s^{-1} . The mass resolution is $\Delta M = 0.4 \text{ AMU}$ in the mass range 10–50 AMU, and $\Delta M = 1 \text{ AMU}$ for 50–213 AMU. The optimum accumulation time for one mass spectrum is 3.2 s. Two channel electron multipliers, CEM 1 and CEM 2, with different geometric factors, are used to detect the

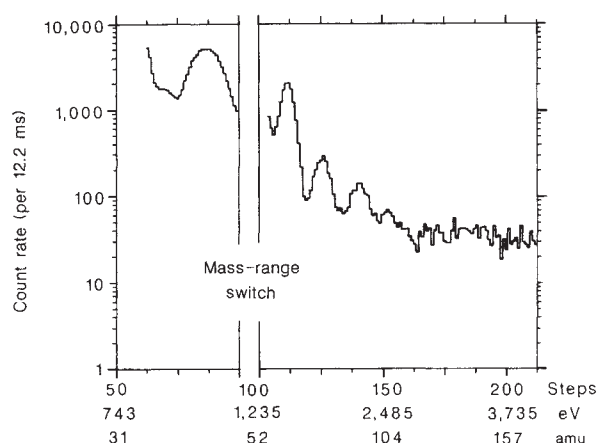


Fig. 2 Count rates per 12.2 ms for ions of mass 40–160 AMU, measured from 00:00:17 to 00:00:20 UT on 14 March 1986, at a distance of $\sim 11,000$ km from the nucleus.

ions. CEM 2 is used when the ion fluxes are so high that CEM 1 is in saturation.

The PICCA instrument was switched on 20 h before closest approach. The first cometary ions were detected 4.25 h before closest approach at a distance of 1.05×10^6 km from the comet. The performance of PICCA was normal until a few seconds before closest approach, when the spacecraft signal was lost.

The best mass spectra were obtained during the last 20 minutes. One example is shown in Fig. 1. The data were collected with CEM 1 at a distance of $\sim 27,000$ km from the nucleus, at 23:56:46 UT on 13 March 1986. The count rate per 12.2 ms is plotted against instrumental steps and energy of the various ions. Using the fly-by velocity of 68.4 km s^{-1} , the energies have been converted into AMU. The ions of the H_2O group produce a signal strong enough to saturate CEM 1; the inset shows the CEM 2 data for this group. These spectra clearly reveal the ions of the H_2O group (H_2O^+ , H_3O^+ , OH^+ and O^+), which were expected to dominate the cometary ionosphere². In addition, we see the major ions associated with the CO^+ and CO_2^+ groups, and sulphur (S^+) which are all generally observed in the plasma tails of comets. Ions of larger atomic mass are also present, as shown in Fig. 2, which is a mass spectrum between 40 and 160 AMU. This spectrum was recorded at a cometocentric distance of $\sim 11,000$ km. Peaks are observed close to 64, 76, 94, and above 100 AMU, which may correspond to heavy metals of the iron group, to sulphur compounds (S_2^+ , CS_2^+) and to various hydrocarbons. In order to discriminate between these

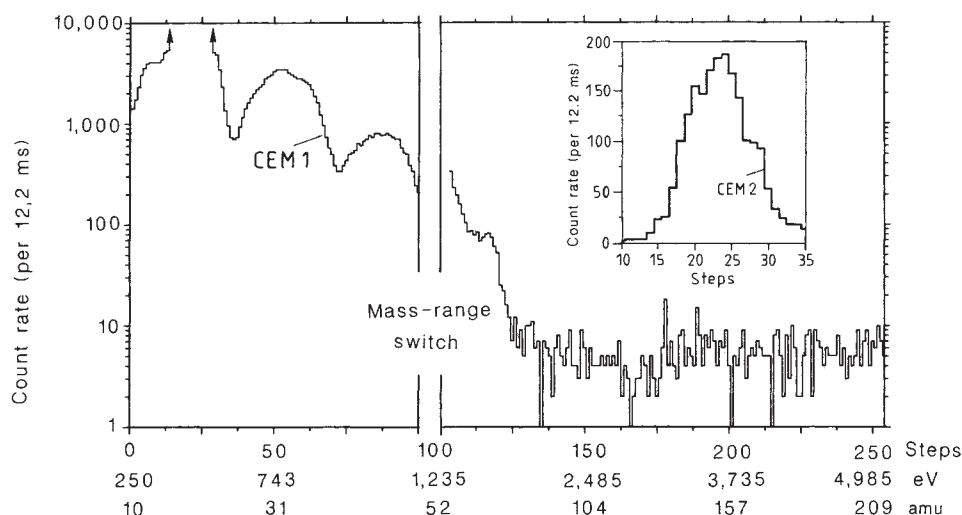


Fig. 1 Count rates per 12.2 ms detected by CEM 1 plotted against energy or atomic mass (AMU). In the region of the H_2O group, CEM 1 is saturated; the inset shows the H_2O group measured with CEM 2. These spectra were obtained on 13 March 1986, from 23:56:46 to 23:56:49 UT, at a distance of $\sim 27,000$ km from the nucleus.

possibilities, we must compare the observations with the results of detailed model calculations; such calculations are now in progress.

Besides the chemical identification, we can use those spectral features which are uncontaminated by neighbouring species and thus very clear in appearance (especially those at higher mass) to construct the ionospheric thermal profile. This will be useful for comparison with model calculations, in order to understand the basic thermodynamics of the cometary atmosphere/ionosphere. It will also enable us to estimate the positions of the ionopause and the 'inner shock' should the latter exist. We are

currently working on this important problem.

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Composition of comet Halley dust particles from Giotto observations

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Mass spectra of cometary dust particles measured by the PIA dust particle analyser aboard the Giotto spacecraft show some unexpected and striking features. First, small particles below 10^{-14} g are much more abundant than anticipated by models. Second, most of the particles are rich in light elements such as H, C, N and O, suggesting the validity of models that describe the cometary dust as including organic material. Third, the light elements specifically seem to have a low ratio of mass to volume. Three examples of original mass spectra showing typical compositions are given; these have been measured and are compared with a computer-simulated mass spectrum.

The PIA instrument is a time-of-flight mass spectrometer, described in ref. 1. When a solid particle hits the target in front of the spectrometer, ions are formed, and those containing a positive charge are mass-analysed. Impacts are detected by the total ion charge released and by the impact light flash. Electronics and microprocessor controls carried by the spacecraft allow the instrument to adapt to the varying cometary environment as well as to produce data compression. An adjustable aperture varies the target area exposed in order to keep the impact rate to below 100 s^{-1} , the instrument's limit. Special care has been taken to keep the experimental design as close as possible to that of the corresponding PUMA instruments aboard the Vega spacecraft. Both instruments are described in greater detail elsewhere^{2,3}.

The design of the instrument incorporated assumptions concerning: (1) the number and size distribution of particles that would hit the instrument's target; (2) the chemical and physical nature of cometary dust particles; (3) the physical process which leads to the formation of positive ions on particle impact.

For estimating the dust emission of the comet, we used the model given in ref. 4, choosing a target area of 5 cm^2 . We expected that for the close fly-by, impact rates on the target area would reach several thousand per second, and so we used an adjustable orifice, which could vary the surface area from 500 mm^2 to 1 mm^2 according to the impact rate. This area range was sufficiently large to record impacts during early parts of the fly-by but it could also be reduced to take into account increases in the comet's activity and the instrument's ability to handle only up to 100 impacts per second.

To establish a pre-flight model for cometary dust particles, we assumed that physically they resemble the so-called 'Brownlee particles'⁵, which have a fluffy structure, and that chemically they are similar to type C1 carbonaceous chondrites.

As there are no facilities for accelerating particles of the entire range of possible sizes to the encounter speed of 68 km s^{-1} , models for the physics of ion formation had to be extrapolated from measurements at the Heidelberg dust accelerator using

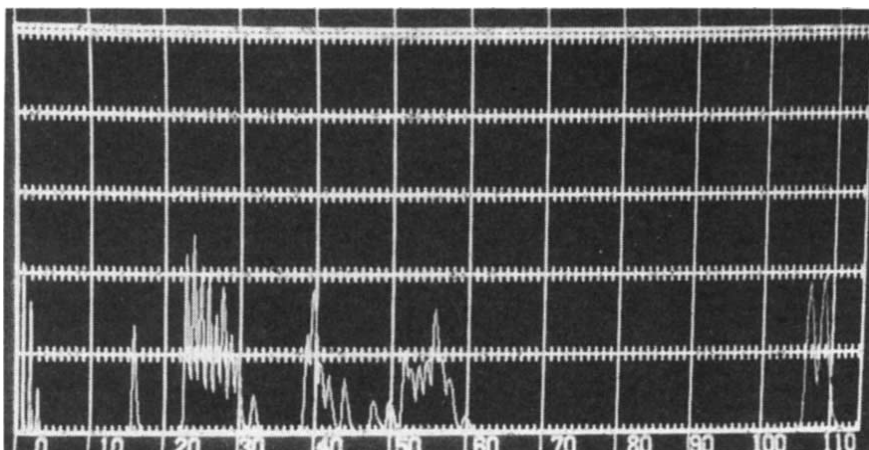


Fig. 1 Computer-simulated mass spectrum of a dust particle of $0.5 \mu\text{m}$ diameter and density 2 g cm^{-3} as it hits the PIA target, using the composition of a piece of an interplanetary particle determined by X-ray analysis. Intensities are plotted logarithmically, in arbitrary units; horizontal lines indicate factors of 10. See text for further explanation.

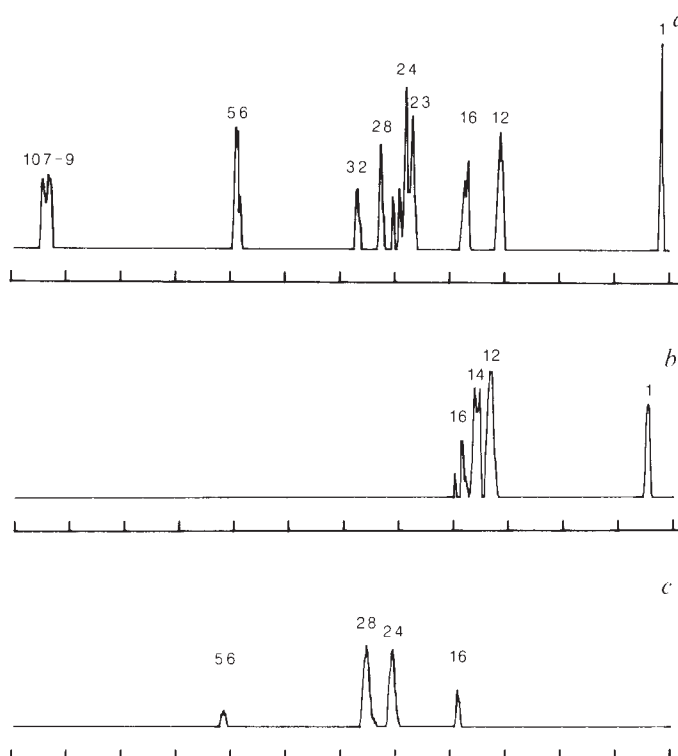


Fig. 2 Time-of-flight spectra of three cometary particles measured by PIA (internal reference numbers 33116 (a), 32778 (b) and 33675 (c)). Vertical scale is logarithmic; peaks are labelled with mass numbers.

iron particles of $1\text{ }\mu\text{m}$ diameter. One approach numerically models the kinematics of the impact. These analyses provide values for pressure and temperature during different phases of an impact. Assuming thermal equilibrium (at least locally), the degree of ionization for the various elements can be calculated using a Saha equation⁵. From this assumption, many at least doubly charged ions would be expected at the Giotto impact speed. An alternative model assumes ion formation by desorption⁶. To accommodate both possible cases, PIA was equipped with a 10% silver-doped, $10\text{-}\mu\text{m}$ -thick platinum foil target, PUMA-1 (on Vega 1) had a corrugated silver target plate, and PUMA-2 (on Vega 2) a $10\text{-}\mu\text{m}$ silver foil target.

The instrument performed perfectly during function tests carried out in a fully operational configuration during cruise. It also functioned as expected during and after the encounter.

Because the operation of the instrument was fully automatic, data analysis was extremely complex and the results presented here are therefore only preliminary, being based on unprocessed

raw data. The number of silver ions (from the target) is a measure of the mass of the incident particle; the ratio of target ions to projectile ions is according to ref. 2, a measure of projectile density (mass per unit volume of the envelope); for the impact speed of Giotto an increasing ratio is associated with decreasing density. From the data, we estimate that most of the particles have masses of the order of 10^{-16} g , much smaller than predicted from the pre-flight dust models in which particle densities were taken to be of the order of 1 to 0.1 or even below. As described in refs 1 and 2, only $\sim 3\%$ of all the data are transmitted in the so-called 'mode 0', the mode directly accessible for mass number allocation and assessment of instrument performance. However, in this mode the instrument works like a transient recorder at 15 MHz, which means that mass lines may not have been sampled at their peak. Three examples were selected from all the mass spectra to illustrate these results.

The structure of the mass spectra shown in Fig. 2 is partly affected by the instrument characteristics. The logarithmic intensity scale indicates relative abundance only. Figure 1 is a computer simulation of a mass spectrum as it would be measured by PIA if a piece of interplanetary dust particle of diameter $0.5\text{ }\mu\text{m}$ and density 2 g cm^{-3} (see ref. 4) hit the target. (Note that the light elements are not accessible to X-ray analysis.) Figure 1 does compare well with the flight mass spectra shown in Fig. 2a, b; however, the number of hydrogen ions H^+ , H_2^+ and H_3^+ seems to be overestimated in our model compared with the flight data.

The mass spectrum in Fig. 2a is characterized by lines showing (apart from the contribution made by the target material Ag at 107 and 109 AMU) strong peaks at 12, 16, 23, 24, 28 and 56 AMU, respectively indicating the presence of C, O, Na, Mg, Si and Fe.

The mass spectrum shown in Fig. 2b is composed entirely of low-Z elements; that in Fig. 2c is consistent with a particle having a pure silicate composition. Examination of the mass spectra, including those taken in modes with higher data compression, revealed no trace of the doubly-charged Pt target ions, and indeed the contribution of target ions to the mass spectrum generally seems to be much lower than expected. Care must be taken when interpreting the mass spectra because, particularly in the case of particles of medium mass, molecular ions and atomic ions may contribute to the same peak.

It is striking that $\sim 80\%$ of all spectra seem to be of the type shown in Fig. 2. In general the spectra compare well with those obtained by the PUMA instruments on the Vega missions. They suggest that the cometary particles are only roughly similar to type C1 carbonaceous chondrites, as they contain both light elements and silicates, as described by several models (see for example refs 7, 8). No gross isotopic anomalies have been detected. However, more information should become available after detailed analysis of further data.

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Dust density and mass distribution near comet Halley from Giotto observations

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The dust impact detection system (DIDSY) carried by the Giotto spacecraft has measured the density and mass spectrum (in the range 10^{-20} – 10^{-8} kg) of the dust near comet Halley. Profiles of the dust spectrum obtained at a distance of 291,000 km from the Halley nucleus show a complex mass spectrum, depleted in intermediate and small masses. Near closest approach (~600 km from the nucleus), the dust activity increases dramatically and the spectrum is dominated by larger masses. The cumulative mass index (for a mass distribution function of the form $m^{-\alpha}$) measured at an approach distance of 2,200 km from the nucleus is $\alpha = 0.66 \pm 0.05$, corresponding to $\alpha = 0.83 \pm 0.05$ at the nucleus. The Halley dust surface emission rate is found to be typically 1×10^{-6} kg m $^{-2}$ s $^{-1}$ for masses $\leq 10^{-8}$ kg, corresponding to a total dust production rate of 3.1×10^3 kg s $^{-1}$. Particle fragmentation may have occurred in the dust cloud. Most of the mass striking Giotto resides in the few large particles penetrating the dust shield, and the integral mass is estimated to be ≤ 150 mg. Although the existence of previously unexpected small particles (of mass 10^{-20} kg) implies that previous infrared dust modelling¹ must now be extended, these particles are found to contribute negligible areal cross-section compared with larger (≥ 10 μ m diameter) particles. Momentum balances and energy considerations applied to an observed deceleration suggest that a large mass of the spacecraft was detached by an impact and ejected at low velocity.

DIDSY uses five independent subsystems for the determination of the cometary dust mass spectrum. (Fig. 1, and see ref. 2 for a complete description). The first subsystem (MSM) comprises three piezoelectric sensors fixed to the spacecraft front dust protection shield: two of these (DID2 and 3) are operated in a variety of coincidence modes, while the third (DID4) operates independently. The second subsystem (RSM) uses a piezoelectric sensor fixed to the rear Kevlar dust shield to

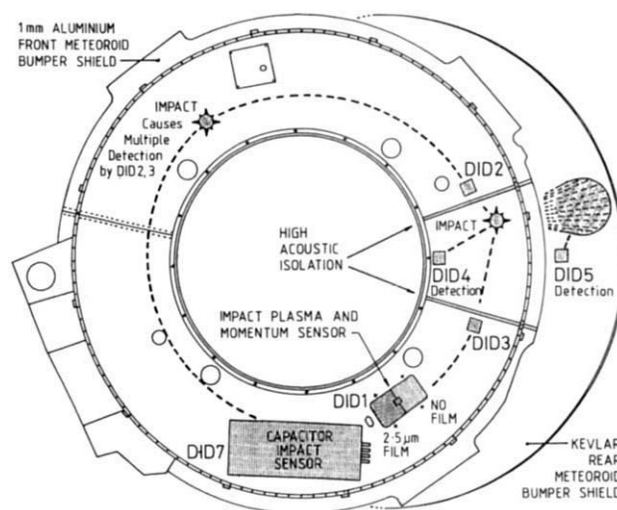


Fig. 1 DIDSY sensor configuration on the outer dust shield and (DID5) on the rear Kevlar shield. Dashed lines show impacts of a small and large (penetrating) particle.

detect those dust grains which penetrate the front shield²⁻⁴. The impact plasma and momentum sensor (IPM) comprises two subunits: the plasma subunit (IPM-P) is located behind an aperture in the front shield and determines the mass of an incident particle by measuring the impact-generated plasma; it is divided into two parts (A and B), one of which is covered by a thin (~2.5 μ m) foil. The IPM momentum unit (IPM-M) uses a piezoelectric sensor fixed to this same target plate and can measure in coincidence. The CIS (capacitor impact sensor), or DID7, incorporates a thin-film capacitor fixed to the front dust shield, operating in a threshold mode.

At encounter switch-on, all monitors were nominal and all dust sensors performed correctly until -16 min (times are relative to closest approach at 00:11 UT on 14 March 1986, ground-station received time). At this time the CIS appeared to suffer a permanent short-circuit; at ~-1 min this fault corrected itself and normal operation resumed. At ~-43 s, data from the IPM-P became erratic and no useful data from that sensor have been recovered for subsequent times. From the same time, the mode of operation of two of the MSM piezoelectric sensors (DID2 and 3), which should have been cyclic, became erratic for a few seconds and then changed to a fixed, non-preferred mode. The effect of this change of mode was to alter the limiting sensitivity and effective area for these sensors; the quality of the data is otherwise unaffected. All of the piezoelectric sensors performed until switch-off. In the last minute before encounter, ~9 s of data were lost, up to -5 s. No data are available after closest approach until +20 s, but during the next 51 s 30% of the data are available. The last event was recorded at +49 min 13 s (201,897 km from the nucleus), by the DID4 sensor.

Table 1 summarizes the main properties of the subsystems and of the ~12,000 impacts so far identified up to the time of closest approach. A small number of impacts have been detected by more than one sensor (for example, CIS and DID2/3 or IPM-P and IPM-M), but these constitute a small proportion of the total number of detected events. Saturation and dead-time effects were significant for the MSM, IPM-M and CIS sensors after ~-30 s. In Table 1 the columns headed 'Number detected' and 'Peak rate' are not corrected for these effects, although the 'Peak flux' has had corrections applied. All data in this table refer to the time period from first impact detection up to -43 s for IPM-P, -5 s for MSM, RSM and IPM-M and -10 s for CIS. Data used elsewhere (Figs 2-4) are corrected for dead-time and saturation effects.

Calibration of all subsystems at high velocities, and the in-flight coincidence measurement, were essential for the very high

Table 1 DIDSY subsystem characteristics and summary of dust impacts recorded before closest approach

Subsystem	Limiting mass (kg)	Geometric area (m ²)	Effective area (m ²)	First detection	Total no. detected	(s ⁻¹) (Time of peak)	Peak flux* (m ⁻² s ⁻¹)
DID1 (IPM-M)	4×10^{-13}	1.19×10^{-2}	1.19×10^{-2}	-24 min (9.7×10^4 km)	1,027	155 (-8 s)	4.5×10^4
DID1 (IPM-PA) (sensor open)	10^{-20}	5.96×10^{-3}	5.96×10^{-3}	-62 min (2.5×10^5 km)	1,100	31 (-49 and -44 s)	5.2×10^3
DID1 (IPM-PB) (sensor + foil)	10^{-20}	5.96×10^{-3}	5.96×10^{-3}	-36 min (1.5×10^5 km)	80	10 (-47 s)	1.6×10^3
DID2/3 } (MSM)	(+2.5 μ m foil) 4×10^{-12}	1.94	$2.5 \times 10^{-1}\dagger$	-65 min (2.7×10^5 km)	1,465	63 (-26 s)	1.5×10^3
DID4 }	4×10^{-12}	2.2×10^{-1}	$1.56 \times 10^{-1}\dagger$	-70 min (2.9×10^5 km)	906	39 (-28 s)	5.2×10^2
DID5 (RSM)	10^{-9}	2.2	$\sim 0.4\dagger$ (Est.)	-208 s (1.4×10^4 km)	11	3 (-7 s)	7
DID7 (CIS)	3×10^{-13}	10^{-1}	10^{-1}	-34 min (1.4×10^5 km)	7,551	726 (-28 s)	5.3×10^4

Est., estimate.

* For all masses above the limiting mass.

 $\dagger$ Depends on incident mass spectrum (see text).

reliability attached to incident particle mass assignment. IPM-P was calibrated at 67 km s^{-1} (ref. 3 and J. R. Goeller, personal communication) and IPM-M and DID2-5 up to 7 km s^{-1} (ref. 5).

The largest grain so far detected in the data arrived at -44 s and had a mass of $\sim 40 \text{ mg}$. This was a penetrating dust grain which was detected by all three front-shield piezoelectric sensors. Much earlier, at -21 min, an impact occurred on the IPM, which caused both the IPM-M and IPM-P sensors to saturate. This is the only such saturating event so far identified in the IPM data, and implies an incident mass of $\geq 5 \times 10^{-11} \text{ kg}$. Note that full-amplitude data (termed 'discrete', and which allow a highly accurate mass determination to be made) are transmitted for only a limited number of impacts.

Three sensor subsystems (DID2/3, DID4 and DID7-CIS) all show peaks in their respective count rates at ~ -28 to -26 s . In fact, when a correction is applied to take account of the fact that the DID2/3 mode of operation was changing during this time, all three of these systems showed their maximum count rate in the same data frame (of duration 1.13 s) at -28 s. The IPM-M shows a small local maximum in the count rate in this frame, but also shows a much higher rate in the data from the period -8 to -5 s.

If the dust grains are ejected from the nucleus predominantly in the direction normal to the surface, and if dust emission is confined largely to the sunlit hemisphere of the nucleus, then one would expect a major increase in the impact rate on the spacecraft $\sim 23 \text{ s}$ before closest approach, corresponding to the time at which the spacecraft crosses the dawn terminator. Before this critical time, only the 'reflected particles'; that is, those already driven away from the Sun by radiation pressure, would be encountered. CCD (charge-coupled device) imaging on 13 March at 18:23 UT with the Anglo-Australian telescope using a replica of the Halley Multicolour Camera red continuum filter (730 nm) (S. F. Green and D. W. H., in preparation) showed jets originating from position angles of 160, 110 and 30° (measured east from north, projected on the sky). Giotto, approaching from a position angle of 116° , could have crossed the first of these immediately before closest approach. A more sophisticated approach must take into account the distribution of discrete dust sources at the time of encounter, but the fairly close coincidence of these times may prove to be of special significance.

As the spacecraft swings by the comet, the dust detection system records particles from various areas of the nucleus surface. In fact, even at a given point of the spacecraft's trajectory the encountered particles do not come from the same area because the particle velocity is mass-dependent. Thus, particles

do not necessarily arrive at the spacecraft in the order of their ejection, and this effect combines with the nucleus rotation to juxtapose particles from different source areas. In addition, the particle ejection-velocity vectors must display a certain distribution. Both Halley Multicolour Camera images of the emanating jets⁶ and modelling of ground-based observations of dust features in the coma⁷ suggest that motions of dust particles ejected from discrete sources are highly organized, but it is unclear whether this is also true for particles from the rest of the nucleus surface. It is believed that the transverse component of the momentum that is transferred from expanding gas to dust particles is generally random and its net effect is near zero except in the case of a strong lateral gradient of the gas pressure near the nucleus surface. The smallest of grains (detected by the IPM-P sensor) could share this lateral motion.

The first impacts of particles in the range 10^{-17} to 10^{-12} kg were recorded at distances of $\sim 10^5 \text{ km}$ from the nucleus, whereas both smaller and larger particles were first detected at distances of $2.5\text{--}3 \times 10^5 \text{ km}$. Cumulative mass distributions (shown as a function of time) illustrate the fluxes detected at Giotto (Figs 2, 3). They are used to derive the differential mass distribution, and hence the geometrical area distribution of detected particles and the mass distribution of incident particles per decade inter-

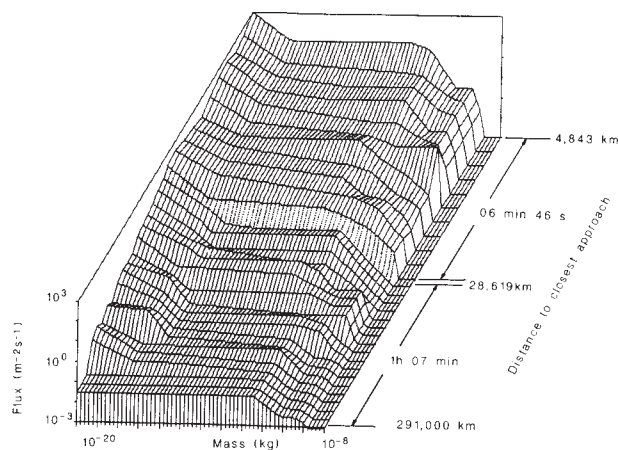


Fig. 2 Cumulative flux and mass spectrum established from DIDSY's subsystems from 291,000 to 4,843 km. Note the 10-fold expansion of the time axis after 4,843 km. A smaller envelope for the lighter particles is revealed by the plateau for these masses near closest approach.

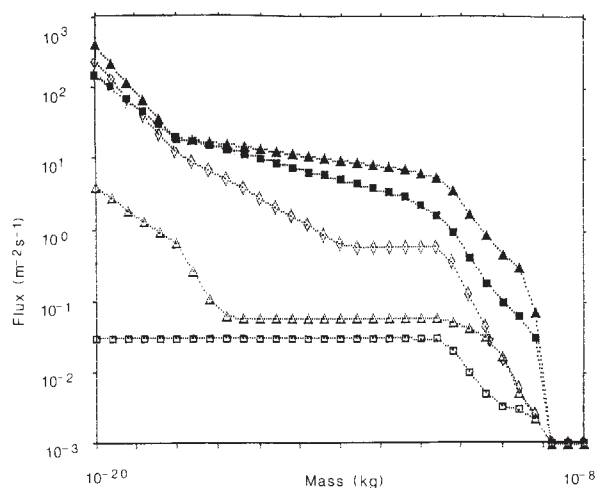


Fig. 3 Cumulative flux distributions established from all DIDSY sensors for the mass range 10^{-20} – 10^{-8} kg, for various distances from (before) closest approach. $\blacktriangle$, 6,374 km; $\blacksquare$, 15,627 km; $\diamond$, 28,619 km; $\triangle$, 167,678 km; $\square$, 291,191 km.

val of mass (that is, from mass m to $10m$); these are computed for five sample points in each decade interval at times dependent on flux rate changes, and have been shown to be accurate to 10% using test data. The integrated mass intercepted by the spacecraft and fractional area of erosion as a function of time are calculated for masses up to 10^{-8} kg.

Examining a small but significant period of data (see Fig. 4) for evaluating the integrated mass detected by DIDSY sensors, we relate this to the Giotto Radio-Science experiment's deceleration measurement from 00:10:14 to 00:10:44 UT which determined an average decelerating force of 0.7 N (ref. 8) and an integrated deceleration of 3.15 cm s^{-1} ; this compares with the total measured deceleration of 16.67 cm s^{-1} (ref. 9). Closely related to the mass calibration of the DIDSY piezoelectric sensors is the momentum enhancement factor⁵, ϵ ; this factor also determines the spacecraft deceleration. For penetrating particles greater than a critical mass $\bar{m} = 10^{-9}$ kg (ref. 4), an ϵ value of 11 is used⁵; for penetrating particles the retention of momentum in the 1-mm dust shield is derated according to $(\bar{m}/m)^{2/3}$. For the latter, the enhancement of momentum is close to unity if the spacecraft shield confines the gas generated in such an impact 'explosion'.

The cumulative impact flux distribution for the interval from 3,168 to 1,259 km is:

$$\Phi = 2.5 \times 10^{-6} m^{-0.66} \text{ m}^{-2} \text{ s}^{-1}, 10^{-13} \text{ kg} < m < 10^{-8} \text{ kg} \quad (1)$$

We integrate this to find the total incident mass from limits $m_{\min}$ to $m_{\max}$:

$$M = \int_{m_{\min}}^{m_{\max}} \frac{\partial \Phi}{\partial m} m \, dm = 5.0 \times 10^{-6} [m^{0.33}]_{m_{\min}}^{m_{\max}} \quad (2)$$

As the dependence on $m_{\min}$ is weak, we find that the mass approximates to $5.0 \times 10^{-6} (m_{\max})^{0.33} \text{ kg m}^{-2} \text{ s}^{-1}$.

Of special interest is the integral beyond the maximum mass recorded by DIDSY. The low value of the mass index ($\alpha = 0.66$, equation (1)) shows that the significant mass is confined to the larger masses—perhaps even a single particle. Integration (by equation (2)) to the largest likely particle in this period (8 mg) yields a total intercepted mass (during this period) of 12 mg. Although this is almost one magnitude smaller than that required for the Radio-Science experiment's observed deceleration⁸, one exceptionally large particle (40 mg) was detected near the start of this period (00:10:16 UT). The impact of an additional large particle not encompassed by the average flux relationship might reconcile these data.

Although the concentration of masses near the single largest event is an important discovery, we cannot readily account for more than ~ 150 mg during the entire encounter unless the missing data near closest approach show an exceptional increase. Without momentum enhancement, the total deceleration requires ~ 1.3 g: such discrepancies cannot be alleviated by reducing ϵ (thereby increasing the masses assigned to the particles observed by DIDSY), because this would reduce the deceleration effect by a similar amount.

Energy considerations could also argue (less strongly) against the impact of a total mass of 1.3 g. With 3.6×10^6 J incident energy and $\sim 10\%$ partitioning of heat into the dust shield (of thermal capacity $8 \times 10^3 \text{ J K}^{-1} \text{ m}^{-2}$), heating of the shield would lead to a temperature rise of ~ 24 K. Although the measured dust-shield temperature rise is indeed 20 K near DID1 and DID2, gas heating based on a Halley gas production rate of 5×10^{29} molecules s^{-1} (refs 10, 11) can account for such a rise without requiring particulate impacts. The eroded area on Giotto is calculated as $\sim 0.11\%$ for the period until closest approach, assuming typical impact parameters at 69 km s^{-1} (refs 4, 12); however, fine abrasion by small particles (of $\sim 10 \mu\text{m}$ diameter) in the dust jet after closest approach could exceed this figure by a large fraction.

Considering the implications of the very low mass index for the spacecraft deceleration and the question of the 'missing mass', we must examine the possibility of some special momentum enhancement but only for the few (or possibly only one) large masses. We consider the partitioning of a fraction a of the incident particle energy $\frac{1}{2} m_i v_i^2$ into part of the spacecraft body, a sensor or a component (of mass M) which is then accelerated by gas pressure¹² to a velocity V . By equating $\frac{1}{2} M V^2 = a \cdot \frac{1}{2} m_i v_i^2$, the momentum enhancement is simply $\epsilon = a v_i / V$. If a is only 5%, and impact occurs at a place where the pressure is confined, such as behind the dust shield or especially in the motor unit (1-mm Al cover and fully enclosed), the enhancement would be $0.05 \times 68,000/100 = 34$. This mechanism could enhance the effect of the estimated incident mass of 100 mg to twice that required to account for the deceleration of 16.6 cm s^{-1} during the encounter. This situation would require detachment of a

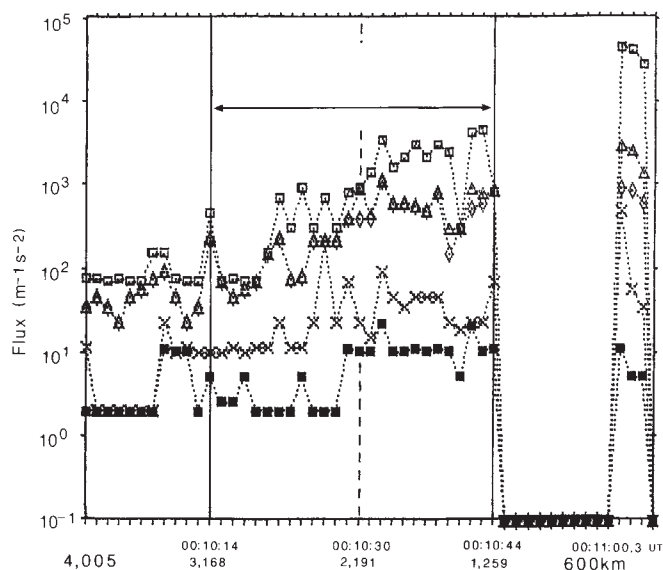


Fig. 4 Cumulative flux plotted against time before closest approach (and distance to the nucleus) for various mass intervals, measured by IPM-M. $\square$, $>4.0 \times 10^{-13}$ kg; $\triangle$, $>1.4 \times 10^{-12}$ kg; $\diamond$, $>3.8 \times 10^{-12}$ kg; $\times$, $>5.8 \times 10^{-11}$ kg; $\blacksquare$, $>3.8 \times 10^{-11}$ kg. Radio-Science experiment data⁸ are available for the period 00:10:14 to 00:10:44 UT (indicated by an arrow) and indicate an average decelerating force of 0.7 N during this interval.

component of mass ~ 4 kg in the forward direction at 100 m s^{-1} ; at 200 m s^{-1} velocity, however, the enhancement would be $\varepsilon = 17$ and the detached mass 1.1 kg in total. The change in Giotto's spin axis due to loss of mass⁹ also demands a significant shift of the spacecraft mass distribution, but can be accounted for by a missing 600 g at the periphery.

Considering the astrophysical implications of the flux spectrum, observed before closest approach we note that the index of 0.66 at Giotto closest approach corresponds to a comet source mass index of 0.83, still implying an increasing contribution from the very largest masses (see Table 2).

We can use equation (2) to deduce the total nucleus dust emission rate using modelling based on particle dynamics¹⁵: a rate of $1.7 \pm 0.5 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ is measured for the DIDSY detection range ($m \leq 10^{-8} \text{ kg}$), but we must integrate up to the maximum mass capable of leaving the nucleus. Although this

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Table 2 Particle distribution indices for comet Halley dust, before closest approach

Index	At Giotto trajectory (2,000 km)		At Halley nucleus	
	Determined	Predicted ¹⁶	Derived*	Predicted ¹⁶
Cumulative mass (α)	0.66 ± 0.05	0.90	0.83 ± 0.05	1.07
Differential mass (α)	1.66 ± 0.05	1.90	1.83 ± 0.05	2.07
Differential size (u)	2.98 ± 0.15	3.70	3.49 ± 0.15	4.20

* Assumes a predominance of the 'direct' nuclear emission and velocities according to the Halley environmental model¹⁶. The DIDSY data from after closest approach, representing a different and very active part of the nucleus, show a strong enhancement of smaller particles (differential size index $u = 5$ –7, locally).

parameter has yet to be determined from the observations of Halley, predictions and models^{13,14} have used a value of $3.3 \times 10^{-6} \text{ kg}$. With this limit (and the integral depends only on the one-sixth power of the limit), a total Halley dust output of $3.1 \times 10^3 \text{ kg s}^{-1}$ is obtained.

The mass distribution observed before closest approach has significant implications for the optical scattering data,¹⁵ obtained from rearward-viewing instruments, because it implies only a weak contribution to scattering by smaller masses ($\leq 10 \mu\text{m}$ in diameter). Camera data⁶ (forward-viewing) must be related to the data obtained after closest approach (not yet analysed). Although this effect can yield a higher total dust output for Halley (which may remain undetected from remote observations except by radar¹⁶), near-nuclear infrared observations of Halley reveal a mass output near closest approach of $2 \times 10^4 \text{ kg s}^{-1}$ (M. S. Hanner and N. G. Tokunaga, personal communication), a value comparable to our result. For an H_2O production rate of $5 \times 10^{29} \text{ molecules s}^{-1}$ (M.S.H. and N.G.T., personal communication), the gas production rate of $1.5 \times 10^4 \text{ kg s}^{-1}$ is some five times the dust production rate, supporting a moderate dust content for Halley at this time.

Although the DIDSY data show a size distribution different from that predicted by previous modelling, it remains to be established whether this is invariant throughout the coma or whether (as the low index could indicate), particle fragmentation later produces the optical scatterers required by analysis of images⁷, thereby reducing the index α as a result of this process. The existence of particles three orders of magnitude lower in mass than particles of the 'cut-off' size (10^{-7} m radius) used in infrared dust modelling¹ is amply demonstrated by the particles detected on the IPM-P sensor; however, the (local concentration) area cross-section is negligible compared with dimensions of $\geq 10 \mu\text{m}$ diameter.

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Optical probing of comet Halley from the Giotto spacecraft

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The Halley optical probe experiment (HOPE) aboard the Giotto spacecraft has provided the first measurements of the optical properties of the dust and of some gaseous species (CN, C_2 , CO^+ and OH) from inside the coma of comet Halley. The dust spatial distribution, inferred from sunlight scattering, obeys an r^{-2} law for distances from the nucleus $r \geq 2,000 \text{ km}$. The more rapid increase of dust density with distance observed in the innermost coma probably reflects the presence of a jet, or a surge of activity within a few hours before closest approach. The CN and OH signals increase more slowly than the dust signals, but faster than predicted by a simple model (of solar-excited resonance fluorescence) for the distribution of these species¹. This effect is probably caused in part by the dust contribution, as well as by the production from parent molecules of OH and CN in an excited state.

The optical probe experiment² relies on the fact that the difference between two consecutive measurements of the spectral radiance is the spatial derivative of the radiance along the line of sight. If one assumes that the coma is optically thin and that steady state is reached between two consecutive measurements, this difference is directly proportional to the light scattered by the dust or emitted by a gaseous species inside a small volume element centred on the moving probe.

The instrument is a refracting photopolarimeter³ which measures linearly polarized brightnesses in the direction opposite to the direction of motion. Sunlight reflected by the cometary dust is measured in three gas-free emission bands (blue, green and red); the light emitted by OH, CN, C_2 and

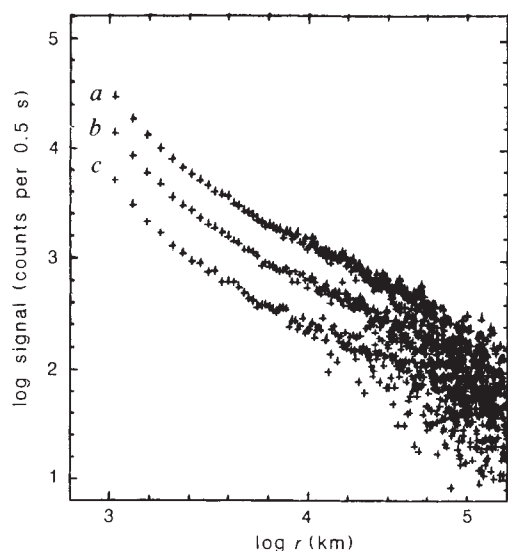


Fig. 1 Evolution of the integrated continuum (dust) signals in the green (*a*), blue (*b*) and red (*c*) channels as a function of the distance *r* to the nucleus. A slight departure from the r^{-1} variation expected from an r^{-2} dust spatial distribution law can be detected close to the nucleus.

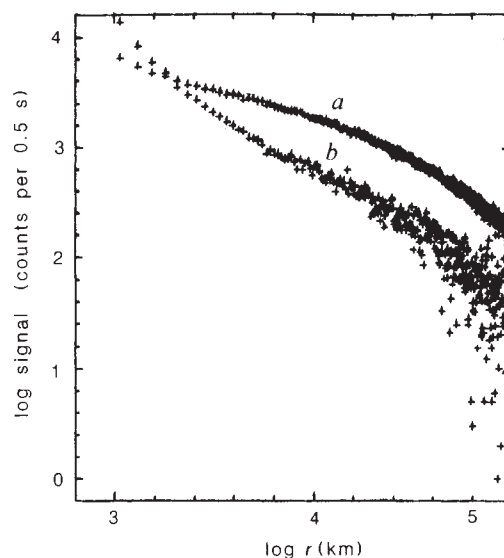


Fig. 2 Comparison of the evolution with distance to the nucleus *r* of integrated signals in the CN channel (*a*) and in the dust blue channel (*b*).

CO^+ (Table 1) is recorded in four additional channels. The spectral discrimination is achieved by imaging seven uniformly illuminated interference filters onto a microchannel detector plate. The filter mosaic, designed to provide comparable signal levels in all channels, is deposited on the objective lens ($f/1.7$, 18 mm diameter). The field-of-view diameter is 3° . A polaroid analyser is placed in front of each filter except the CO^+ one; the polarization is determined by the rotation of the analyser with the spin of the spacecraft. During a spin period of 4 s, eight consecutive measurements of 0.5 s each are simultaneously made in the seven channels at eight different clock angles.

Such an instrumental design—with no moving parts but nevertheless capable of simultaneously measuring seven emissions and six polarizations—implied some hazard of cross-talk between the various channels (diffusion inside the filter mosaic, misalignment between optics and detector, electronic cross-talk). In the event, the cross-talk matrix, inferred from calibrations, was found to have coefficients of $<3\%$. The loca-

The instrument was switched on for the first time on 13 September 1985. The on-board calibration source, mounted on the back of the baffle cover, allowed us to check the stability of the instrument response. The cover was removed on 9 October 1985, by means of a pyrotechnic device. During the cruise phase, a significant decrease in the stray light level was observed as the antenna phase angle neared its closest-approach value. Immediately before closest approach, the stray light (plus background sky radiation) level was low in clock sectors 2, 3 and 4 (~ 250 counts per 0.5 s in the OH and CN channels), moderate in clock sectors 0, 1 and 5 (850 counts per 0.5 s), and high for clock sectors 6 and 7 (7,000 counts per 0.5 s). Immediately before and during closest approach, the dark count was negligible because the detector was operating at -20°C .

HOPE was switched on again at 20:06 UT on 13 March 1986, at a distance of $\sim 10^6$ km from the nucleus. All channels were operating at their nominal expected performance. The experiment was turned off at 03:31 UT on 14 March, when the out-bound spacecraft was $\sim 850,000$ km from the nucleus. A partial loss of telemetry had occurred after closest approach; however, the instrument was soon found to have survived the closest approach without damage.

The stability of the stray light level during the first part of the fly-by allowed us to monitor the evolution with time (or distance to the nucleus) of the integrated radiances, from which local radiances can be derived. The first OH and CN emissions were detected at $\sim 200,000$ km from the nucleus; dust was first detected at $\sim 50,000$ km. All signals started to rise dramatically at distances $<10,000$ km.

Figure 1 shows an example of the raw data. Each integrated dust signal (in the blue, green, and red channels) is sampled every 4 s in clock sector 3 and, after subtraction of the stray light, plotted as a function of the distance to the nucleus (*r*) from 100,000 km (25 min before closest approach) to 600 km (closest approach). The distance to the nucleus was calculated assuming a spacecraft velocity of 68.373 km s^{-1} and a closest approach time of 00:03:04 UT. The three signals evolve nearly in parallel, and obey very nearly an r^{-1} variation, which is what is expected from an r^{-2} dust spatial distribution law when the spacecraft is not too close to the nucleus⁴, according to our simulations. In these simulations, the solar flux scattered along the rearward-looking line of sight by a model dust distribution^{5,6} had been integrated every 0.5 s, taking into account the partial

Table 1 HOPE spectral response

Filter	Central wavelength (nm)	Bandpass, 50% peak (nm)	Bandpass, 1% peak (nm)	Transmission
Dust, blue	442.3	4.7	9.0	0.46
Dust, green	577.1	9.8	20.0	0.73
Dust, red	717.5	3.4	7.5	0.39
OH	311.3	5.4	10.0	0.23
CN	387.5	3.7	10.0	0.37
CO^+	424.9	3.6	8.0	0.51
C_2	514.5	3.6	6.0	0.70

tion of this rearward-looking instrument on the top platform of the spacecraft implied some hazard stray light from specular reflections from spacecraft components. This stray light, the importance of which was assessed during the solar simulation testing sequence, was found to be modulated by the rotation of the instrument around the Giotto spin axis. The instrument baffle was optimized for the specific Earth-comet-Sun geometry prevailing at the time of the encounter. The net result of these design and implementation choices was a relatively lightweight (1.3 kg) multi-photopolarimeter, well protected from the adverse conditions of the encounter (rearward-viewing and entirely dust-shielded).

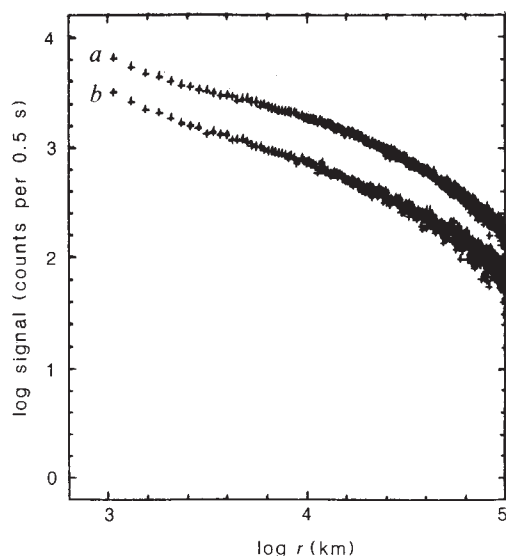


Fig. 3 Comparison of the evolution with distance to the nucleus r of integrated signals in the CN (a) and OH (b) channels. The OH signal starts to increase before the CN signal.

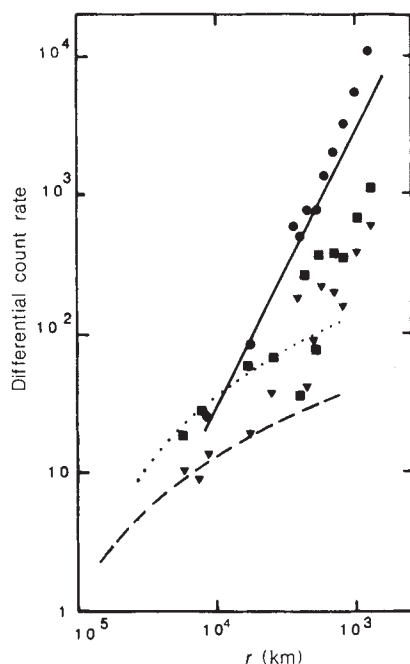


Fig. 4 Evolution of the differential count rates for the dust green channel (●), the OH channel (▼) and the CN channel (■), as a function of distance r to the nucleus. The data may be compared, respectively, with an r^{-2} dust spatial distribution law (solid line), a model of OH emissivity through resonance fluorescence (dashed line) and a model of CN emissivity through resonance fluorescence (dotted line).

polarization, the background and some stray light. A preliminary analysis of the dust data reveals a redder dust colour as r decreases, probably indicating a spatial segregation of the grains. Local inhomogeneities seem to be detected for $r < 8,000$ km, possibly due to the traversal of higher-density regions. The evolution of the polarization with r will be extracted from the relative evolution of signals from the various clock sectors.

The evolution of the signal in the gas channels is significantly different from that of the dust channels, as can be seen in Figs 2 and 3. Figure 2 shows the integrated radiance (gas + cometary dust) recorded in the CN channel (a), together with the con-

tinuum signal (cometary dust) in the blue channel (b). Figure 3 compares the OH channel (gas + dust) and CN channel (gas + dust) contributions. Relative strengths cannot yet be derived accurately from the data shown here, because various calibration factors have not been taken into account at this preliminary stage. However, one can see that the OH signal starts to increase before the CN signal. The slight difference in curvature may reflect a difference in lifetime of the parent molecules, the lifetime of the parent of CN being significantly shorter than that of the OH parent. A more refined analysis will allow the clean subtraction of the background, and of the continuum components superimposed on the gas signals, thus allowing the determination of the lifetimes of the radicals.

As stated above, the difference between two consecutive measured count rates is proportional to the local radiance of the coma in the immediate vicinity of the moving probe. In Fig. 4 this differential count rate is plotted for clock sector 3 as a function of r for the green dust channel (dots). The nine points closest to the nucleus are obtained from raw data without any smoothing, whereas for distances $\geq 3,000$ km, some averaging was performed along pathlengths. For this analysis, data from distances $> 20,000$ km were discarded, although good measurements at greater distances will certainly be available in future.

If the comet output were constant over a period of about half a day, we would expect the dust differential count rate to follow an r^{-2} law (solid line in Fig. 4). This is clearly the case for $r > 2,000$ km, but in the region closer to the nucleus, the local emissivity increases faster than r^{-2} . Because Giotto entered Halley's sunlit hemisphere at a distance of 2,050 km, the observed increase is most probably due to the sunward enhancement of dust production. It could also be interpreted as the result of either a jet or a surge in cometary activity. Such rapid activity changes have indeed been observed from the International Ultraviolet Explorer spacecraft before and after the encounter (M. Festou and P. Feldman, personal communication).

Figure 4 also shows the differential count rates for the OH (triangles) and CN (squares) channels (gas + dust). Because the count rates are smaller than those for the dust green channel, the data are somewhat noisier. However both OH and CN show a clear increase of the signal with decreasing distance to the nucleus, at a slower rate than that of the dust signal. For comparison, models of emissivity¹ through resonance fluorescence are plotted, for OH (dashed line) and for CN (dotted line), after normalization to a distance of $\sim 10,000$ km. Clearly, the emissivities increase inward much more rapidly than is predicted by the models. The signal remaining after subtraction of the theoretical contribution of the fluorescent radicals probably results from the combination of the dust continuum contribution in the filter bandpass and some emissive photodissociation. This last emission process has already been observed in comets and has been invoked to explain the presence of the oxygen red line⁷. The presence of OH radicals created in an excited state has been suspected in comet IRAS-Araki-Alcock⁸, and the effect of the presence of such radicals on the measurements carried out by various instruments on the Vega and Giotto spacecraft has been computed⁹. The model for the OH distribution assumes isotropic evaporation of H_2O from the nucleus, whereas camera images show strong sunward dust (and probably gas) emission. However, this should not affect the OH distribution significantly because of the large scale length ($\sim 10^5$ km) for H_2O dissociation and the resulting resonance fluorescence distribution. In fact, asymmetric H_2O emission favours the H_2O emissive dissociation, as Giotto was entering the sunlit hemisphere when approaching the pericentre. The distribution of newly created CN radicals from the photodissociation of various possible CN parents has also been investigated¹⁰, and further analysis of the data presented here will allow us to assess the relative importance of these processes. A precise evaluation of the production of excited CN radicals, combined with the results

of other experiments aboard the space probes, may shed some light on the nature of the unknown CN parent.

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Ion flow at comet Halley

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The three-dimensional positive ion analyser aboard the Giotto spacecraft has been used to study the interaction between protons and α -particles in the solar wind and positive ions from comet Halley. Although the first impression of the overall structure is that the plasma flow evolves smoothly as the nucleus is approached, three sharp transitions of relatively small amplitude can be identified on both the inbound and outbound legs of the trajectory. The outermost one, at $\sim 10^6$ km from the nucleus, appears to be a multiple crossing of a weak bow shock. The innermost one, at 80,000 km, is the boundary where the flowing plasma becomes depleted. On a microscopic scale, the turbulence created by the interaction between the two ion populations extends to a distance of several million kilometres from the nucleus. At Giotto's closest approach to the nucleus, the plasma produced around the spacecraft by dust and gas impacts was much more energetic than had been expected.

On the basis of a study of the plasma tails of comets, Biermann¹ suggested in 1951 that there was a continuous flow of plasma outward from the Sun. The first spacecraft to reach interplanetary space, more than a decade later, found that there was indeed a continuous solar wind. Attention has recently returned to the interaction between a comet and the solar wind, which can now be studied directly by making *in situ* measurements of both solar-wind and cometary ions.

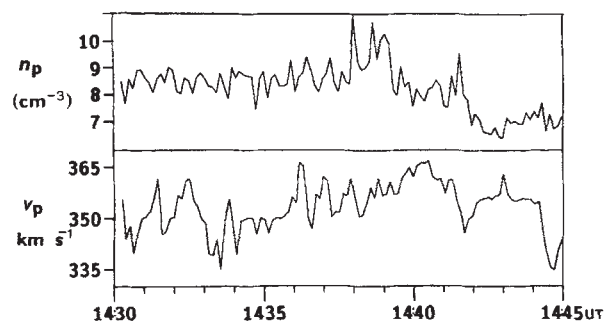


Fig. 1 FIS solar-wind data at a distance of 2.3×10^6 km from the nucleus. The fluctuations in density and velocity caused by the interaction with cometary ions are clearly visible.

The fundamental process involved in the interaction is mass loading of the solar wind by cometary ions. Neutral molecules of cometary origin are ionized by solar radiation within the solar-wind flow at large distances from the comet. Once these relatively massive ions have been implanted in the flow they are accelerated by the interplanetary electric field into cycloidal orbits² moving perpendicular to the magnetic field. The energy and momentum given to the cometary ions comes from the solar wind, which is therefore decelerated by increasing amounts as the comet's nucleus is approached.

There are two fundamental questions to be answered about the interaction process. First, is the deceleration of the solar wind a smooth process involving a gradual deceleration and thermalization of the supersonic flow of the solar wind, or does it occur suddenly by means of a shock wave^{3,4}? Second, do the newly created ions, initially in their cycloidal orbits, interact strongly enough with the solar wind to become subsumed into the flow⁵?

A third question, of concern in the planning and development of the Giotto mission, was whether the measurements of natural plasma would be significantly affected by the interaction of the

Table 1 JPA sensor characteristics

	FIS	IIS
E/q range (keV/e)	0.01-20	0.090-90
Energy resolution $\delta E/E$	4.7%	10%
Geometric factor	$4.7 \times 10^{-3} E$ (eV)	$7.6 \times 10^{-3} E$ (eV)
Acceptance angles		
Azimuthal (deg.)	5	6
Polar zones (deg.)	20-46	15-25
(relative to spin axis)	46-59	50-60
	59-72	85-95
	72-98	120-130
	98-124	155-165
	124-150	
	150-180	

spacecraft itself with the local environment. It had been anticipated⁶ that the bombardment of the spacecraft by neutral molecules and dust particles would create a local plasma which could charge the spacecraft to a positive potential. The JPA instrument (Johnstone Plasma Analyser) was designed to answer these questions and to provide detailed information on the plasma processes involved by measuring the angular and energy distribution of positive ions in the coma of comet Halley.

The instrument consists of two sensors, called the Fast Ion Sensor (FIS) and the Implanted Ion Sensor (IIS), and a Data Processing Unit (DPU). FIS is an electrostatic analyser with a microchannel-plate detector for detecting positive ions in a narrow band of energy/charge ratio which can be swept over a wide energy range. Its main purpose is to observe the solar-wind

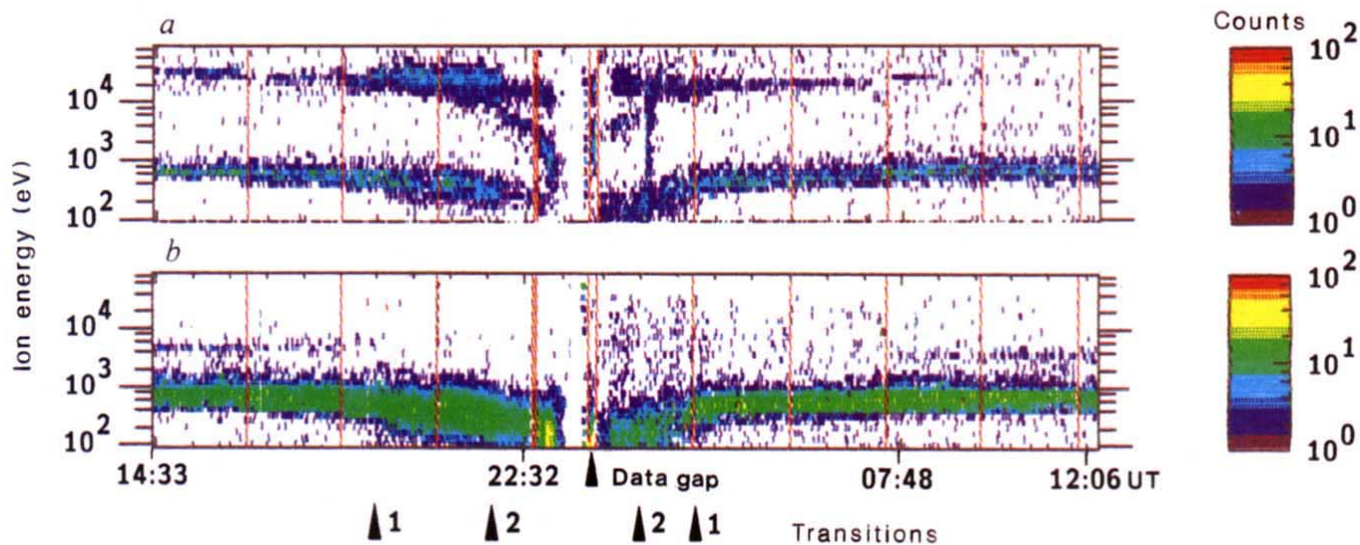


Fig. 2 Data for two mass groups obtained by one IIS time-of-flight sensor, with a field of view $50\text{--}60^\circ$ from the spacecraft velocity vector. The data are integrated over 32 spacecraft spins (128 s). The two mass groups are protons (mass 1 AMU), mainly from the solar wind (b) and implanted cometary ions of mass 12-22 AMU (a). There is a 'ghost' of the proton distribution at the same energies in a, caused by pulse pile-up inside the analyser. Arrowheads mark the positions of two of the transitions described in the text. The data gap begins at the time of closest approach.

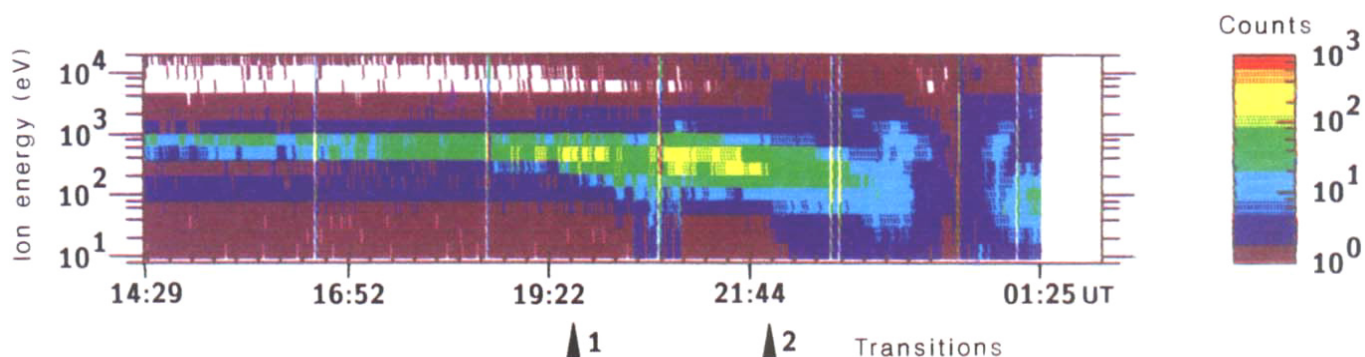


Fig. 3 Data obtained by one FIS angular sector ($20\text{--}72^\circ$ from the spacecraft velocity vector), integrated over one spacecraft spin. It covers the period from 14:30 UT on 13 March, through closest approach, until the sensor ceased to operate. Arrowheads mark the positions of two of the inbound transitions described in the text. Closest approach was at 00:11 UT.

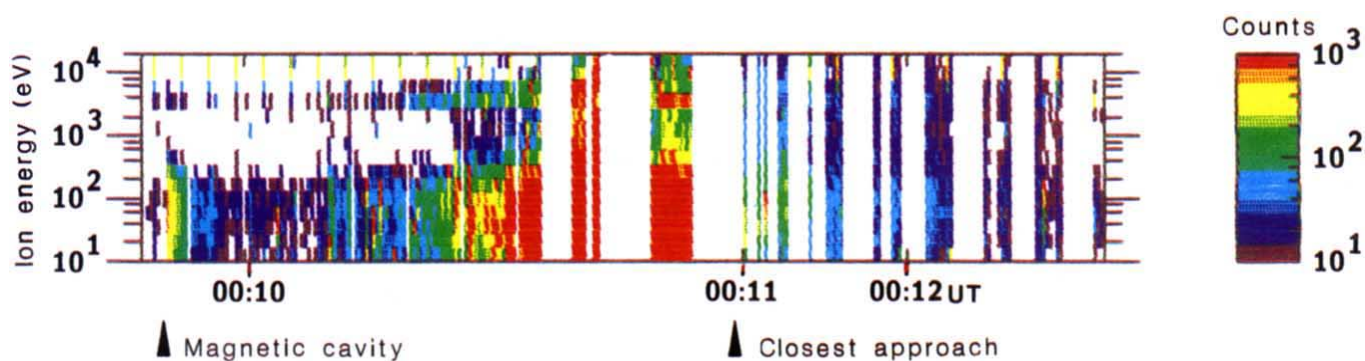


Fig. 4 FIS spectrogram near the time of closest approach, showing the flux of ions detected at the edge of the magnetic cavity and the impact plasma detected 45 s before closest approach. The white spaces are caused by telemetry synchronization loss. A real data gap between 00:11 and 00:12 UT has been closed up in the plot; hence the nonlinear timescale.

distribution from the highly supersonic regime in interplanetary space, through its deceleration and thermalization, to its disappearance at a contact discontinuity close to the nucleus. IIS is an array of five electrostatic analysers followed by time-of-flight analysers. It is therefore able to obtain the mass distribution as well as the angular and energy distribution. Each detected particle is allocated to one of five mass groups by on-board electronics. The purpose of IIS is to observe the cometary ions

implanted in the solar-wind flow. The characteristics of both sensors are listed in Table 1. The operation of the sensors is synchronized to the spin of the spacecraft: FIS obtains a complete distribution in one rotation (4 s); IIS holds each energy level for one rotation and obtains a complete distribution in 32 rotations (128 s). The spacecraft spin axis is parallel to the velocity vector and lies in the ecliptic plane at 73° to the comet-Sun line. Further details of the instrument and its method of

operation are given in refs 7 and 8.

Apart from a brief period of less than an hour on the morning of 13 March, the JPA operated continuously from 43 h before to 26 h after the closest approach at 00:11 UT on 14 March. (All times quoted are ground-station received times.) A number of anomalies occurred as a result of the battering the spacecraft received near closest approach. The IIS high voltage suffered a status change which could not be restored by ground command until 00:41 UT, causing a 30-min gap in the IIS data. At 01:25 UT the FIS high voltage suddenly dropped below the operating level, so that no more data were obtained from this sensor.

The first problem in the interpretation of data on the solar-wind interaction is to separate variations due to cometary structure from temporal variations in the solar wind itself. Fortunately, the solar wind appears to have been steady and relatively slow throughout this period. A preliminary analysis, using IIS data to obtain solar-wind velocity after the closest approach, shows that the velocity varied from 350 km s^{-1} at 14:30 UT on 13 March to 340 km s^{-1} at 10:00 UT on 14 March. Over the same period the density increased from 8.5 to 9.5 cm^{-3} . In fact the level of fluctuation in the solar wind caused by the presence of cometary ions at these times exceeded the difference between these measurements. As there were no large-scale changes in the solar-wind particle parameters, the structure seen in the plasma observations can be taken to be that produced by the comet.

The JPA instrument first detected hydrogen ions of cometary origin at 16:00 UT on 12 March at a distance of $7.8 \times 10^6 \text{ km}$ (approximately one ionization scale length) from the nucleus. The flux increased slowly over the next 24 h. At the same time the solar wind showed a steadily increasing level of wave activity.

A 15-min sample of the waves is shown in Fig. 1, starting at 14:30 UT on 13 March. There are fluctuations in speed of $>30 \text{ km s}^{-1}$ and changes in density (n) with $\Delta n/n > 0.3$. The shortest periods at this time were $\sim 1 \text{ min}$; closer to the nucleus, waves with shorter periods and larger amplitudes were observed. This activity clearly indicates an interaction between the cometary ions and the solar wind⁹, although insufficient for strong coupling.

An overview of the results obtained from 14:30 UT on 13 March to 12:06 UT on 14 March is presented in the two colour spectrograms, Figs 2 and 3. Figure 2 shows data from one of the five analysers in the Implanted Ion Sensor, for two of the five mass groups: solar-wind protons in Fig. 2b and the mass group containing masses 12–22 AMU in Fig. 2a. Due to pile-up in the time-processing channel in the time-of-flight analyser, a 'ghost' of the solar-wind protons appears in Fig. 2a at the same energy as in Fig. 2b. The energy spectrum of the 'ghost' protons is quite distinct from that of the higher-mass particles, and detailed time-of-flight spectra confirm the identification. Note also that the data gap of 30 min caused by the status change at closest approach has been deleted, although its position is marked by an arrow.

At the beginning of the data interval shown in Fig. 2, the cometary ions lie in a fairly narrow energy band at an energy of 32 keV. If the ions are in cycloidal orbits perpendicular to the field, the spectrum, in the spacecraft frame of reference, should appear to be peaked at the maximum pick-up energy. This energy is $4(m/q)E \sin^2 \phi$, where (m/q) is the mass-to-charge ratio of the ion, ϕ the angle between the flow velocity and the magnetic field, and E the flow energy of the solar-wind protons. Taking $m/q = 18$ (water-group ions have been observed to dominate the Halley atmosphere¹⁰), the velocity of the cometary ions is 580 km s^{-1} and the magnetic field direction required to produce this spectrum with a proton flow energy of 640 eV (350 km s^{-1}) is $\phi = 56^\circ$. The velocity of the ions is greater than it would have been merely from being accelerated up to the solar-wind velocity, and is consistent with pick-up into cycloidal orbits perpendicular to the usual direction of the interplanetary magnetic field. The energy of the implanted

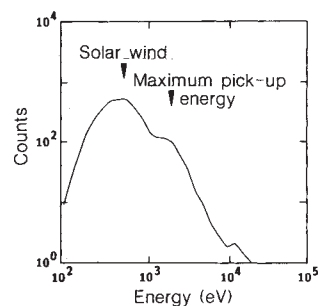


Fig. 5 The spectrum of protons measured by IIS during the period 20:54–21:05 UT on 13 March, just after the spacecraft crossed the first transition (Figs 2, 3). The large fluxes at energies above the maximum pick-up energy are evidence of another acceleration process, such as Fermi acceleration.

cometary ions decreases along with the flow energy of the solar-wind ions as the nucleus is approached.

Figure 3 shows data from the angular sector of the Fast Ion Sensor which views most nearly along the velocity vector. The figure shows the solar-wind flow through to the contact surface and part of the way out. Starting at $\sim 21:44 \text{ UT}$, some implanted cometary ions can be seen at steadily decreasing energies. The plot ends at 01:25 UT when FIS ceased to operate.

The first impression created by these figures is that the interaction is remarkably smooth and nearly symmetrical. As the nucleus is approached, the speed of the solar wind is gradually reduced and its temperature, given qualitatively by the width of the green strip, gradually increases. On the way out the variation is very similar but the intensity appears to be reduced. The latter impression is caused by a change in the direction of the flow so that the peak flux shifted into the field of view of another of the IIS sensors.

There is no obvious discontinuity comparable to the bow shock around a magnetosphere. More detailed examination reveals a number of sharp transitions of relatively small amplitude, at which the characteristics of the distributions change suddenly (in less than 10 min), separating regions in which the characteristics evolve smoothly. In each case a transition corresponding to one observed on the inbound leg can be identified on the outbound leg at the same relative position, although fewer data are available. This gives confidence that the structure is real, and spatial in character. Here we concentrate on the three major transitions, although there are possibly several others.

The first transition was observed to begin at $\sim 19:35 \text{ UT}$. Although this is the least well time-resolved of all the transitions, it involves the largest changes. It has a thickness of $\sim 125,000 \text{ km}$ (30 min). The corresponding transition on the outbound leg ends at 03:16 UT (Fig. 2). The distances from the point of closest approach are $1.13 \times 10^6 \text{ km}$, inbound, and $0.76 \times 10^6 \text{ km}$, outbound. At the transition, moving in the inbound direction the following changes take place: (1) The flow speed decreases from 300 to 260 km s^{-1} . (2) The flow is deflected away from the comet–Sun line. (3) The energy and angular widths of both the solar-wind and the implanted-ion distributions increase.

In detail, the behaviour of the solar wind across the transition is very interesting. The wave activity already mentioned had been increasing in amplitude and frequency of occurrence throughout the day. Between 19:35 and 20:05 UT there are several oscillations (not visible in the figures) in which the speed and density decrease and then recover. After one such oscillation the distribution does not return to its original state but becomes heated. Five minutes later the distribution returns to the fluctuating solar-wind form for another 5 min, before finally retaining the heated state at a reduced average velocity. The appearance is of the double crossing of a weak shock wave with several large precursor waves, the overall position of which is moving in and out. The transition is from a cool distribution, with a

flow velocity varying in magnitude and direction, to a less oscillatory, hotter and, on the average, slower distribution.

After the transition the fluxes of both the solar-wind protons and the cometary implanted ions are significantly increased above the pre-transition energy. Figure 5 shows the energy spectrum of the protons measured by IIS: the flow energy of the solar wind, E , and the maximum pick-up energy, $4E$, are indicated by arrows. Another acceleration process, such as Fermi acceleration¹¹, is needed to account for the large number of protons at energies above the maximum.

The second transition occurs at 22:00 UT inbound and 02:05 UT outbound (Fig. 2). The distances are 0.54×10^6 and 0.47×10^6 km, respectively, and its thickness is $\sim 20,000$ km (5 min). The following changes take place: (1) The direction of flow is deflected further away from the comet-Sun line. (2) The energy and angular widths of the solar-wind distribution increase further. (3) The most striking change takes place in the implanted ion distribution (Fig. 2a). The energy width of the distribution decreases and a second line becomes prominent at a lower energy.

Closer to the comet, the energy of the latter ion population decreases rapidly and can be seen also in the FIS spectrogram (Fig. 3) as it drops to nearly the same energy as the solar wind. As these ions have higher mass, their velocity must be less than the solar-wind velocity. The cometary ions are created locally and picked-up locally. In this region the magnetic field is becoming draped around the comet, so the angle ϕ between the flow and the magnetic field decreases. From Fig. 3, the solar-wind flow energy at 23:30 UT is ~ 90 eV, and the locally created ions peak at an energy of 600 eV. This is consistent with a field angle $\phi = 18^\circ$. The implication of this preliminary result is that, even close to the comet, acceleration is by injection of the ions into cycloidal orbits rather than by frictional interaction with the solar-wind flow. It has been argued¹² that the field in this region would be too turbulent to allow the development of cycloidal orbits.

The third transition occurs at 23:50 UT inbound and 00:29 UT outbound, at distances of 86,000 and 74,000 km, respectively. This is probably not a contact discontinuity, but can be understood as the gradual loss by charge-exchange of the energetic cometary ions and protons¹⁵. (Old cometary ions, with velocities smaller than that of the spacecraft, are outside the field of view of the JPA sensors.

The most dramatic effects were observed in the last minute before closest approach (Fig. 4). At 00:09:35 and 00:09:51 UT two short bursts of ions with energies up to 400 eV were observed, coinciding with the edge of the magnetic cavity surrounding the nucleus¹³. These bursts have relatively wide angular distributions. During the last 45 s before closest approach, the flux increases rapidly until the spacecraft appears to be surrounded by a dense and very hot cloud of plasma. Fluxes increase at energies up to 20 keV, and the particle distributions are nearly isotropic. We consider that this is related to the plasma produced by the impact of dust and neutral particles on the spacecraft, although the energies are very much higher than had been anticipated⁶. The time at which the fluxes start to increase, 00:10:15 UT, is the same time at which an increase in the dust particle impact rate is observed¹⁴. We cannot be sure from these preliminary data whether there was a significant amount of charging of the spacecraft, but there is no obvious signature in our ion data. The data gaps in Fig. 3 were the result of the deflection of the spacecraft's antenna beam caused by the impact of large dust particles.

We dedicate this paper to the memory of Professor L. Biermann, who initiated the study of cometary plasma physics in 1951 and who, sadly, died before these observations were made. We acknowledge the support of the SERC, the Max Planck Gesellschaft zur Förderung der Wissenschaften, the Bundesminister für Forschung und Technologie, the Swedish Board of Space Activities, the Consiglio Nazionale delle Ricerche and NASA.

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Energetic ions in the environment of comet Halley

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The energetic particle experiment, EPONA/EPA, carried aboard the Giotto spacecraft recorded *in situ* measurements of energetic charged particles on the sunward side of comet Halley, from a trajectory very close to the nucleus (closest approach 600 km). Here we present selected observations from the inbound and outbound passes. Preliminary studies suggest the presence on the inbound pass of an ion 'pick-up' region ($\sim 6 \times 10^6$ km in extent) and a region inside the bow shock ($< 10^6$ km in extent) where possible signatures of mass loading were evident. Acceleration by the pick-up process in the solar wind is inadequate to explain the energies of the observed ions.

The EPONA instrument is described in detail in ref. 1. Briefly, it consists of three semiconductor telescopes, Te1, Te2 and Te3, designed to study ions and electrons with energy $E \geq 20$ keV. The geometric factor for each telescope is 8.1×10^{-2} cm² sr. Te1 was oriented at 45° to the spin axis of the spacecraft and thus viewed in the backward hemisphere with respect to the spacecraft-comet velocity during encounter. Te2 and Te3 were oriented at 135° to the spin axis, and thus viewed in the forward hemisphere. This arrangement, combined with the spin of the spacecraft, allows three-dimensional studies to be made of the distributions of particles of various species recorded in the cometary environment. Because Te2 incorporated a suitable absorbing foil, the difference in count rate between Te2 and Te3 enables ions and electrons to be differentiated. Particle energies were determined by measuring their energy loss in the solid-state detectors in various energy intervals¹ with a time resolution of 0.5 s. It should be noted that the instrument does not resolve heavy-ion mass for mass number $A > 4$. Throughout the time interval covered by the observations discussed, the spin period of 4 s was divided into quadrants, each of which was further subdivided into an odd and an even sector. Counts were made in all three telescopes, alternating between Te1 and (Te2 + Te3) for the odd and even sectors respectively. Only data obtained by Te1 and Te3 in selected energy channels are presented here.

Energetic ions produced by the interaction between comet Halley and the solar wind were observed throughout an extended interval around the point of Giotto's closest approach (00:03 UT, 14 March 1986). Figure 1 shows 4-min spin-averages of the ion

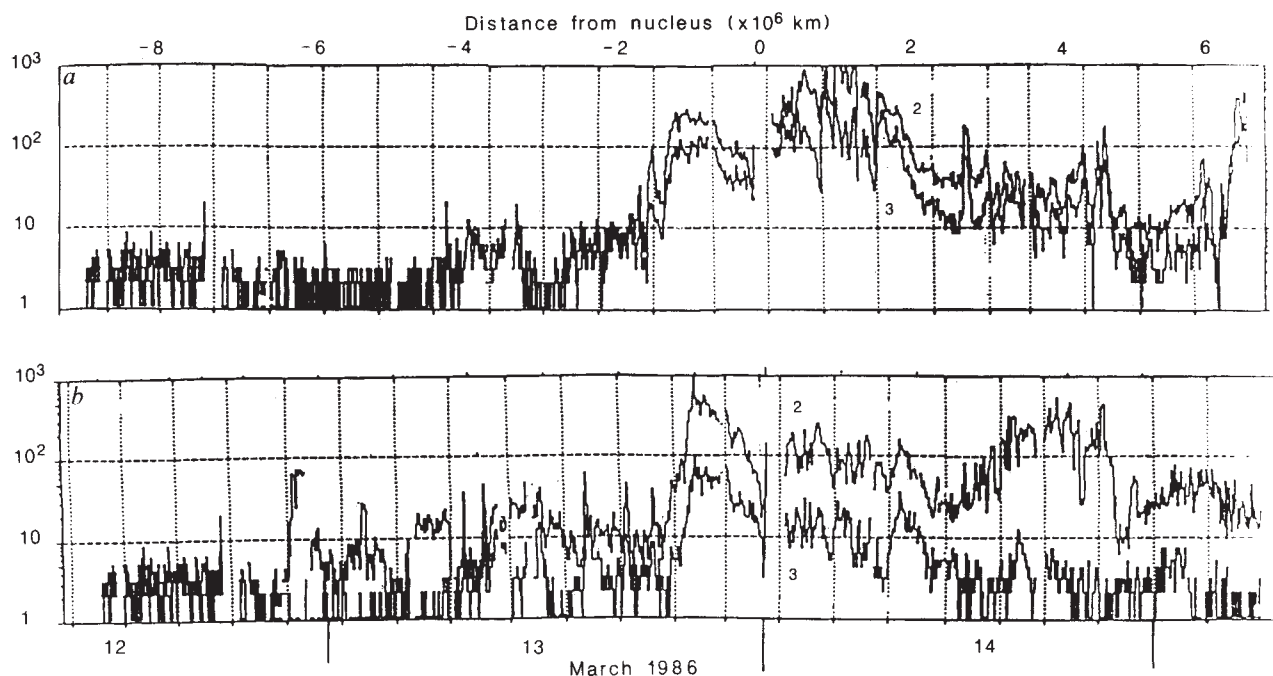


Fig. 1 Ion fluxes (arbitrary units) measured in channels 2 and 3 of telescopes Te1 (a) and Te3 (b), during the period from ~12:00 UT on 12 March to ~03:00 UT on 15 March 1986. Energy intervals for protons: channel 2, 45–75 keV; channel 3, 80–125 keV. Equivalent energy intervals for H_2O^+ ions: channel 2, 100–145 keV; channel 3, 145–270 keV.

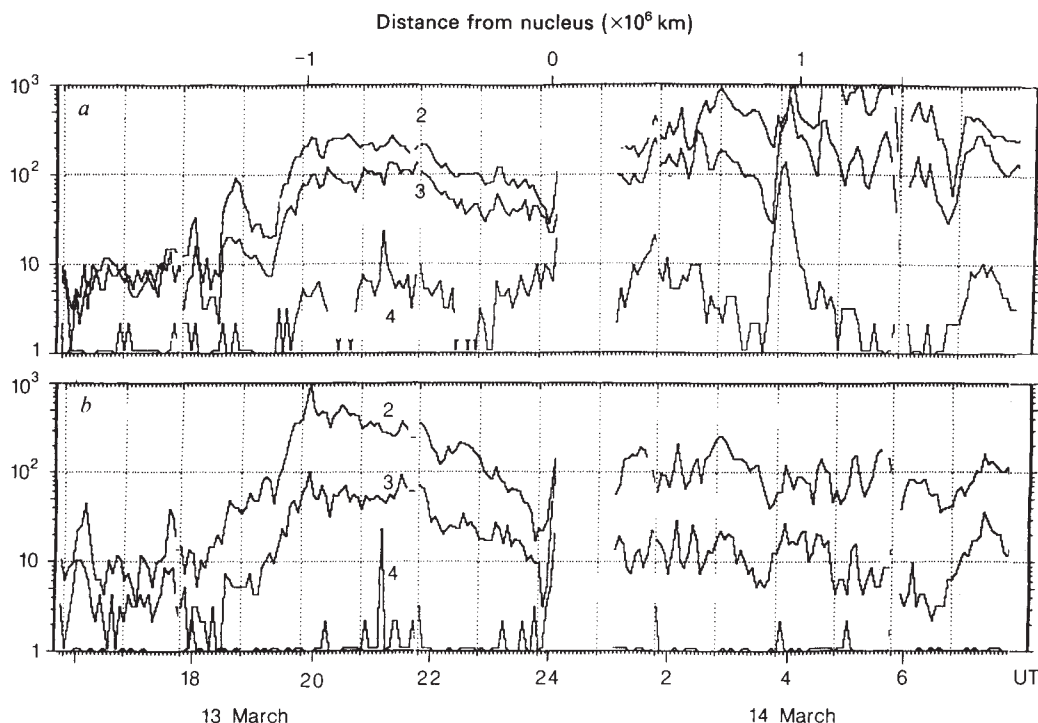


Fig. 2 Ion fluxes (arbitrary units) measured in channels 2, 3 and 4 of telescopes Te1 (a) and Te3 (b), during a period of ~16 h centred on closest approach, which was at ~00:03 UT on 14 March 1986. Te1 and Te3: channel 4, 0.22–3.5 MeV for protons; channels 2 and 3 as in Fig. 1.

fluxes for channels 2 and 3 of both Te1 and Te3, covering the period between ~12:00 UT on 12 March and the end of the Giotto telemetry coverage at ~03:00 UT on 15 March. The first clear ion intensity enhancement was detected by Te3 at ~18:00 UT on 12 March at a distance of $\sim 7.5 \times 10^6$ km before closest approach, and the fluxes were still strongly enhanced when EPONA was switched off at a distance of $\sim 6.75 \times 10^6$ km beyond closest approach.

Three distinct regimes are evident in the particle data recorded during the inbound pass. First, there is an 'outer region' extending from $\sim 1.5 \times 10^6$ to $\sim 7.5 \times 10^6$ km from the nucleus, characterized by large, irregular flux variations accompanied by anisotropies (observed in the sectorized data) that exceeded an

order of magnitude during the peak ion intensities. These are present in the data from both Te1 and Te3. The peak fluxes were detected in those sectors closest to the spacecraft–Sun line; that is, the ions were streaming in the anti-sunward direction.

Second, an 'intermediate region' is found, extending from $\sim 0.1 \times 10^6$ km to 1.5×10^6 km from the nucleus (see Fig. 2, in which 4-min, spin-averaged fluxes for channels 2–4 of both Te1 and Te3 are shown). This region encompassed the interval where the main magnetic field and plasma effects were observed^{2,3}. The ions were characterized by an overall intensity profile which varied relatively smoothly and contained some of the highest fluxes observed during the Halley encounter. The spacecraft's entry into the intermediate region was marked by a more-or-less

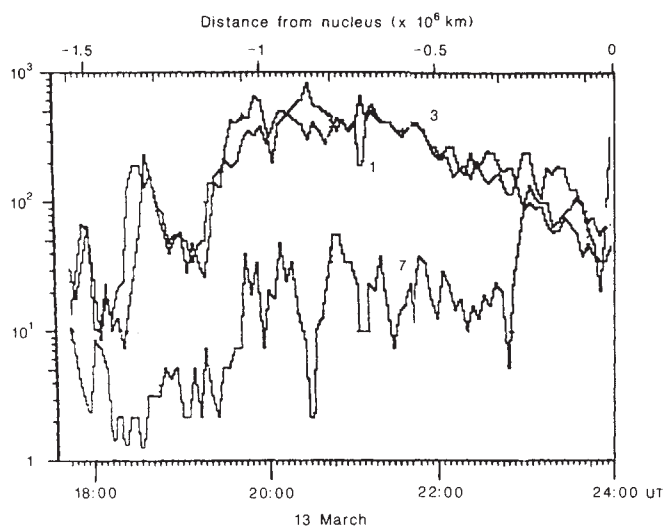


Fig. 3. Ion fluxes (arbitrary units) measured in channel 2 of telescope Te1 for selected sectors, over a period from ~18:00 UT on 13 March 1986 to the time of closest approach (00:03 UT). Sectors 1 and 3 record ions flowing in the anti-solar direction; sector 7 is closest to the direction of comet Halley. Energy intervals for channel 2 as in Fig. 1.

steady increase in ion intensity starting at ~18:00 UT, reaching a peak in Te3 and a quasi-plateau in Te1 at ~20:00 UT. The inward crossing of the bow shock had occurred at ~19:40 UT (ref. 2). The ion intensity then decreased nearly continuously, almost until closest approach. The overall ion distribution became less anisotropic with time in this region (see for example, Fig. 3), showing an increase in count rates from the direction of the comet.

Third, the period from ~23:45 UT on 13 March to ~01:00 UT on 14 March, which includes the closest approach, comprises an 'inner' region, which is characterized by dramatic fluctuations in count rates over several orders of magnitude. These data are not illustrated here and await detailed study to assess the possible influence of telemetry losses and dust impact.

During the outbound pass, strong particle intensity fluctuations were recorded (Figs 1, 2). Preliminary analysis of the magnetic field observations² shows two candidate bow-shock crossings at 03:07 and 07:10 UT on 14 March. Short-timescale intensity fluctuations as well as dramatic spikes were present in the particle data extending over this time interval and beyond. In addition, there were significant variations in the directional characteristics of these particles which persisted until the end of the outbound pass. A comparison between structures identified during the inbound and outbound passes will be the subject of a future study.

Owing to the extremely low gravity of a typical cometary body, neutral molecules and atoms subliming from the surface can escape freely into space with a velocity of ~1 km s⁻¹. These molecules are first subjected to various chemical reactions in the inner coma, and then, farther out, to a variety of photodissociative and ionizing processes (see, for example, ref. 4). The ionized particles are then picked up by the solar wind, they gain energy in the crossed electric and magnetic fields and are convected away in the anti-sunward direction. The increase in energy is proportional to the ion's mass so that for typical solar-wind velocities, the maximum energy gain is a few keV per AMU: that is, ~70 keV for water-group ions.

The nature and origin of the particle enhancements discussed in the previous section and their varying directional characteristics have yet to be studied in depth. However, there are already some indications, mainly the predominance of particle flow in the anti-sunward direction in the outer region of the inbound

pass, that we have observed 'pick-up' ions in the undisturbed solar wind. Furthermore, the decline in the particle fluxes starting at ~0.5 × 10⁶ km from the nucleus in the intermediate region may represent that point in the cometary atmosphere where the mass density of the pick-up ions approaches that of the ambient plasma and the solar-wind velocity is significantly reduced. This interpretation is consistent with the observation of pick-up ions in the environment of comet Giacobini-Zinner^{5,6}; suggest the present data that the pick-up region for comet Halley is more extended than that for Giacobini-Zinner by a factor of ~7. We note that the inward bow-shock crossing at ~19:40 UT on 13 March, as reported by the Giotto magnetometer experiment team², coincided closely with significant particle enhancements recorded by Te1 and Te3 (see Fig. 2). The distance of ~10⁶ km from shock to closest approach is an order of magnitude greater than that observed at comet Giacobini-Zinner⁷.

Water-group ions (O⁺, OH⁺, H₃O⁺) have been identified as the predominant species in the outer atmosphere of comet Halley by several instruments of the Giotto mission⁸⁻¹⁰. Thus, ions of the water group are expected to be the dominant pick-up species. However, estimates of the energies that these and other typical ions may be expected to acquire from the solar wind pertaining at the time of encounter show that the pick-up process is insufficient to account for the observed fluxes of high-energy particles and therefore additional acceleration mechanisms must be postulated. For example, Ip and Axford¹¹ have recently discussed the possibility of second-order Fermi acceleration in plasma turbulence surrounding the comet which could accelerate water-group ions to at least 300 keV.

We thank all those who contributed to the EPONA experiment; in particular, W. I. Axford, H. Rosenbauer, A. Richter, E. Keppler, H. Saeger, W. Tappart and M. Martin. We thank J. Noyes, H. Nye, A. Parkes and D. Ryan for support received at ESOC; B. Franke and P. Zetzsche of IDA, Braunschweig; C. Berner, J. Credland, D. Dale, J. Raistrick and H. van Bekkum of the Giotto Project and Project Scientists R. Reinhard and G. Schwehm. Finally, we thank the NBST, Ireland for a grant.

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Comet Halley-solar wind interaction from electron measurements aboard Giotto

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Measurements made by the three-dimensional electron spectrometer of the RPA-Copernic experiment aboard the Giotto spacecraft give a preliminary description of the complex interaction between comet Halley and the solar wind. As Giotto

approached the comet, it traversed several regions of differing plasma characteristics: a large ($\sim 10^7$ km) upstream region, a foreshock, a bow wave with its apex at $\sim 4 \times 10^5$ km, a transition region, a region permanently and strongly contaminated by cometary ions, a collisionopause at a sub-solar distance of $\sim 5-6 \times 10^4$ km, and various inner regions up to the inner coma, including a region of depleted hot plasma.

One of the two instruments of the RPA-Copernic experiment¹ consists of a spectrometer (the electron electrostatic analyser, RPA1-EESA) designed to measure the three-dimensional distributions of electrons with energies between 10 eV and 30 keV. This instrument includes a symmetrical quadrispherical electrostatic analyser of novel design² and provides 4π (solid angle) electron measurements with high sensitivity and good energy, angular and time resolutions. The analyser has a $360^\circ \times 4^\circ$ field of view, and the spacecraft spin allows the aperture to scan the 4π solid angle twice per revolution; that is, every 2 seconds. The detection system consists of a ring-shaped fast-counting microchannel plate (MCP) which delivers pulses collected on 17 anodes defining 16 angular sectors (giving an angular resolution of $\sim 22.5^\circ \times 4^\circ$) and the ram sector. By varying the analyser high voltage, a 39-step energy spectrum is obtained every 250 ms. The sensor is designed to measure the flux and spectra from $4 \times 10^3/E(\text{keV})$ to $4 \times 10^9/E(\text{keV})$ ($\text{cm}^2 \text{ s sr keV}^{-1}$). An on-board microprocessor is used to compute the symmetry axis of the electron momentum flux tensor, which generally coincides with the magnetic field direction. The three-dimensional electron distribution is then sorted into two-dimensional pitch angle distributions in real time.

A detailed description of the sensor, its operating modes and the data transmitted has recently been published¹. From the transmitted data, the electron density, temperature and flow speed were computed and displayed in real time by the experiment ground support equipment (EGSE). In addition, the ratio of the minimum to the maximum heat flux along the magnetic field was calculated. These quantities were obtained by integrating over the electron distribution function measured by the instrument. Note that the quantities given in the figures as deduced from the EGSE software are not definitive and will be refined following a more detailed analysis.

The electron spectrometer worked continuously for more than 40 hours before closest approach to the comet, apart from a 75-min interval due to spacecraft manoeuvres ~ 20 h before closest approach. Completely reliable data were received until ~ 3 min before closest approach; during these last 3 min (within 12,000 km of the nucleus), dust impacts and the presence of neutral gas may have affected the count rates of the detector. Because special analysis of these data is required, we postpone discussion of this inner region.

Two seconds before closest approach the spacecraft's telemetry signal was lost. When it returned ~ 30 min later, it was apparent that the electron instrument had received some damage, presumably from dust impact. Data from the post-encounter period also require special analysis and will not be discussed here.

Figures 1 and 2 summarize the main features of the plasma environment of comet Halley as observed by the electron spectrometer RPA1-EESA. For several days before closest approach, the solar wind was relatively quiet. Its flow speed was $< 400 \text{ km s}^{-1}$ and its density was $\sim 5 \text{ cm}^{-3}$.

Figure 1 shows the evolution of the density of electrons with energies between 10 eV and 30 keV (N_T), of their temperature (T_C) as estimated from the slope of the energy spectra near 40 eV, and of the ratio (R_Q) of the heat fluxes parallel and antiparallel to the symmetry direction ($Q_{\min}/Q_{\max}$) for the last 7 h before the encounter.

Several clear features of the comet-solar wind interaction can be seen in Fig. 1:

(1) A bow wave, characterized by a relatively abrupt jump in density, is detected at a spacecraft-comet distance of $\sim 1.15 \times$

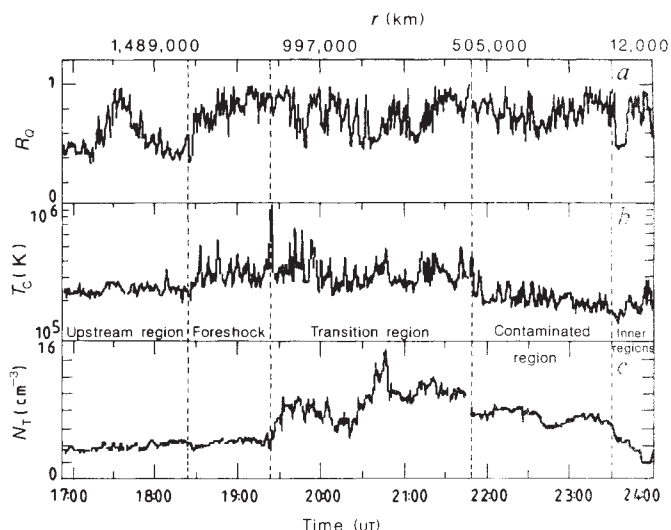


Fig. 1 Values of electron parameters measured during the last 7.1 h on the day before the Giotto closest approach to comet Halley (00:03 UT on 14 March 1986). a, R_Q , the ratio of minimum to maximum heat flux computed parallel and antiparallel to the magnetic field direction; b, T_C , the temperature estimated from the slope of the energy spectra near 40 eV; c, N_T , the density of electrons with energies greater than 10 eV. Times shown are UT at the spacecraft (spacecraft event time); r, distance of Giotto from the nucleus.

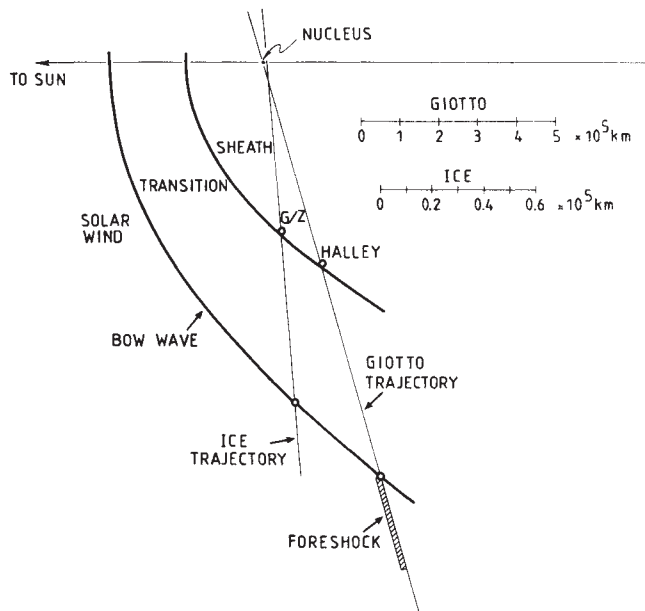


Fig. 2 Comparison of the size of the comet Halley and comet Giacobini-Zinner solar-wind interaction regions. The bow wave, the transition-sheath boundary and the distance scale appropriate to each comet are shown. The plane of projection is defined by the spacecraft trajectory and the Sun-comet direction.

10^6 km ($\sim 19:22$ UT). Taking into consideration the expected flaring of the bow wave and the fly-by geometry (the Giotto trajectory was at an angle of $\sim 107^\circ$ to the Sun-comet line) we estimate the stand-off distance of the bow wave (that is, its distance from the nucleus in the sunward direction) to be $\sim 4 \times 10^5$ km, which corresponds to a total production rate of neutrals, $Q_n \approx 1.9 \times 10^{29} \text{ s}^{-1}$ if the shock Mach number, $M_s \approx 2$, and $Q_n \approx 2.8 \times 10^{29} \text{ s}^{-1}$ if $M_s \approx 1.5$ according to the model of Mendis *et al.*³.

To compare the size of the comet Halley and comet Giacobini-Zinner solar-wind interaction regions, Fig. 2 shows a curve to represent the locations of the bow-waves of the two comets. We assume the boundaries of both solar-wind interaction regions

to be given by an equation of paraboloidal form with a flaring factor of 2, and then use the bow-wave crossing points of Giotto at Halley and ICE (International Cometary Explorer) at Giacobini-Zinner⁴ to determine a , the stand-off distance of each comet's bow wave. For Giacobini-Zinner, $a \approx 6 \times 10^4$ km and for Halley $a \approx 4 \times 10^5$ km. The linear factor relating the solar wind-comet interaction regions of the two comets at the time each was observed is thus in the range 6–7, this difference being mainly due to a larger neutral production rate from the Halley nucleus. The two bow waves are represented by a single curve in Fig. 2, with different distance scales, as shown.

(2) A large turbulent region extends upstream of the bow wave for $\sim 5 \times 10^6$ km from the nucleus. Here fluctuations in the electron distribution occur, characterized by abrupt variations in the electron heat fluxes, with R_Q often reaching a value of unity; that is, equal forward and reverse heat fluxes. Outside this turbulent region the effects of the comet interaction on the solar-wind heat flux are clearly observed out to at least 7.5×10^6 km, when the magnetic field direction points toward the comet region. Increases in the heat flux ratio are observed more than 10^7 km away from the nucleus, probably due to the presence of the comet.

The heat flux ratio appears to provide a sensitive indicator of comet-related disturbances in the solar wind. This ratio is ~ 0.3 in the undisturbed solar wind at this time, but increases to ~ 0.4 at a spacecraft-comet distance of 5.5×10^6 km and never falls below this value inside this distance. As the bow wave is approached this ratio shows rapid fluctuations, often reaching unity, although there are periods relatively free from fluctuations. A heat flux ratio near unity indicates that electrons may be streaming back along the interplanetary magnetic field, in the direction opposite to the heat flux from the solar corona. This is illustrated in Fig. 3, which shows a pitch-angle distribution of electrons during a connected event (Fig. 3b) in comparison with the undisturbed solar-wind distribution (Fig. 3a). About 1 h before the bow wave is crossed, the heat flux ratio rises to near unity, the electron temperature increases by $\geq 50\%$ and becomes highly variable, and the electron density shows fluctuations of several tens of per cent. This region could coincide with a foreshock. These enhanced heat flux ratios and temperatures persist through the bow wave crossing, but they show no large change at the bow wave itself.

(3) After the bow-wave crossing, Giotto entered a transition region characterized by strong fluctuations in the electron density and still larger fluctuations in temperature. This region extended from 19:22 to $\sim 21:50$ UT, that is, from 1.15×10^6 to 5.5×10^5 km from the nucleus (Fig. 1). The average density increases toward the comet, whereas the average temperature is nearly constant. In this region the electron distribution functions may fluctuate rapidly from solar-wind-like to nearly isotropic, which explains the variation of R_Q between 0.45 and 1.

Inside this transition region, low-energy ions are intermittently detected in the ram direction by the RPA2-PICCA detector¹.

(4) Between 21:50 and 23:29 UT, that is, between 5.5×10^5 and 1.4×10^5 km from the nucleus, Giotto crossed a region in which the average electron density and temperature decrease slightly, and fluctuate less strongly than in the transition region. The ratio R_Q is everywhere greater than 0.57, showing that the electron distribution functions are more isotropic than in the transition region. Here low-energy ions are continuously detected in the ram direction by the PICCA sensor.

Bame *et al.*⁴ identified two broad regions behind the bow-wave of comet Giacobini-Zinner and referred to them as the transition region and the sheath. According to their analysis the transition region is characterized by gradual increases in electron density and temperature, and by decreasing flow speed. The sheath is the region in which the density and temperature decrease while the flow speed continues to decrease.

Because of the similar behaviour observed by Giotto and ICE behind the bow waves of the two comets, we have compared

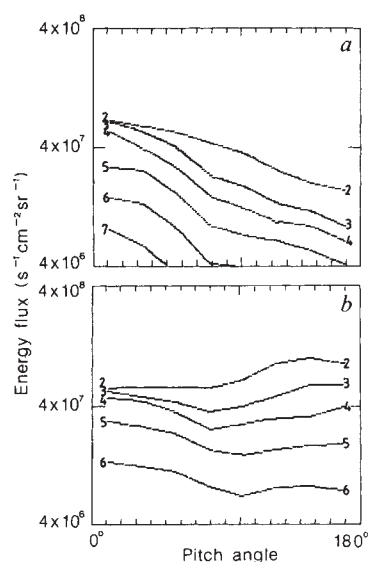


Fig. 3 Examples of pitch-angle distributions of electrons with energies from 55 to 366 eV for *a*, undisturbed quiet solar wind (12 March 1986, 01:49:43 UT; $R_Q \approx 0.3$) and *b*, comet-environment-connected event showing counterstreaming electron fluxes (12 March, 06:32:45 UT; $R_Q = 1$). Numbers 2–7 denote energy channels: 54.8, 71.1, 86.6, 129, 217 and 366 eV. Note that from the three-dimensional electron distributions the direction of the magnetic field can be estimated but not its sign. In case *a*, a pitch angle of 0° corresponds to electrons flowing away from the Sun.

the position of the abrupt change in the behaviour of the electron temperature at $\sim 21:50$ UT during the Giotto Halley encounter with the position of the transition region-sheath boundary identified by Bame *et al.*⁴ at comet Giacobini-Zinner. To do this we used the linear scaling factor of 6.67 determined from the bow-wave crossing locations at the two comets. Figure 2 shows the bow wave, the transition-sheath boundary and the distance scale appropriate to each comet. The transition-sheath boundary was constructed by fitting a paraboloid, with the same flaring factor as for the bow wave, to the Giacobini-Zinner transition-sheath inbound crossing point. The position of the abrupt change in electron temperature inside Halley's bow wave (marked 'Halley' in Fig. 2) lies remarkably close to the transition-sheath surface inferred from the ICE data at Giacobini-Zinner ('G/Z'), implying that comet Halley probably also possesses the transition region-sheath structure, and that this structure could well be a feature of all active comets at a distance of ~ 1 AU from the Sun.

(5) At 23:29 UT the electron sensor registered a sudden decrease in density, associated with a minimum of temperature and R_Q . The Q_n value deduced from the bow-wave position implied a 'collisionopause', where the contaminated solar wind is rapidly decelerated by collisions with outflowing neutrals at a sunward distance from the nucleus of $\sim 5 \times 10^4$ km (ref. 3), corresponding to 1.4×10^5 km from the nucleus along the Giotto trajectory. Our electron data seem to confirm the existence of a collisionopause at this distance, as evidenced by the rather sharp drop in the electron density.

From this boundary to 4.5×10^4 km from the nucleus (23:52 UT), the density decreases to a value as low as 2 cm^{-3} while the temperature increases and R_Q again becomes greater than 0.6. Between 23:52 and 23:59:37 UT Giotto entered a depletion region where the hot plasma density is minimum and nearly constant at $\sim 2 \text{ cm}^{-3}$. Simple pressure-balance arguments suggest that the magnetic field is enhanced inside this region. Then from 23:59:37 UT the electron density increases strongly: this signals entry into the inner coma.

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First results from the Giotto magnetometer experiment at comet Halley

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The Giotto magnetometer experiment at comet Halley has for the first time provided magnetic field measurements in all the important spatial regions characterizing the front-side interaction between the solar-wind magnetoplasma and a cometary atmosphere. Upstream waves of cometary origin have been observed at distances of $>2 \times 10^6$ km from the comet, both inbound and outbound. A cometary bow shock has been identified at 1.15×10^6 km inbound on the dawn side and a thick quasi-parallel cometary bow shock outbound. A turbulent magnetosheath has been observed further inside. A magnetic pile-up region has been identified inside 1.35×10^5 km, inbound, and 2.63×10^5 km, outbound, with fields up to 57 and 65 nT, respectively. A cavity region with essentially zero magnetic field has been discovered, with a width of 8,500 km along the trajectory around closest approach.

The encounter of the Giotto spacecraft with comet Halley provided the first opportunity to study all the major spatial regions characterizing the interaction of the magnetoplasma of the solar wind with the cometary atmosphere. In particular, the innermost part of the interaction region was accessible for the first time due to the close fly-by distance of ~ 610 km (ref. 1) from the cometary nucleus.

The instrument uses two sensor systems, a triaxial fluxgate sensor system mounted outboard and a biaxial fluxgate system inboard (see ref. 2 for details). The prime outboard triaxial magnetometer provided magnetic field vectors at a constant rate of 28.24 vectors per s throughout the complete encounter period, from late 11 March 1986 to early 15 March, when the scientific payload was switched off. The data reported here were obtained in a measuring range of ± 256 nT for each component with a digitization uncertainty of ± 0.063 nT.

Because of the special design of the Giotto spacecraft, involving a dust shield for protection against cometary dust particles, no boom could be provided for the magnetometer experiment; this caused substantial magnetic cleanliness problems. The slowly varying part of the spacecraft magnetic field at the outboard magnetometer, of magnitude ~ 7.5 nT, was removed using the spin variation (spin period ≈ 4 s) for the spin-plane components and in-flight techniques together with the cavity field (see below) for the component parallel to the spin axis. In

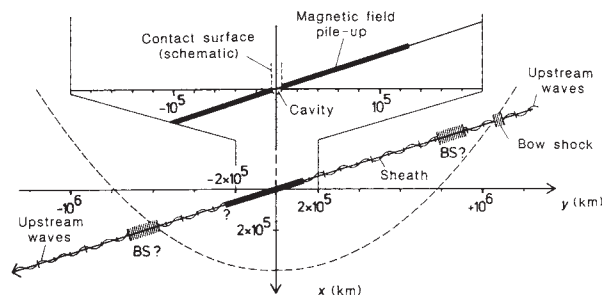


Fig. 1 The encounter geometry of Giotto at comet Halley, with the fly-by trajectory projected on the Halley-centred solar ecliptic x - y plane (see text). The most important interaction regions are marked on the trajectory; the large tick-marks are 1 h apart. A theoretical bow shock shape¹⁷ (dashed line) has been fitted by eye to the bow shock observations. The null field cavity is shown at expanded scale.

addition to the slowly varying spacecraft field, fast variations were caused by the motor despinning the antenna and by the Halley multicolour camera. These stray field problems were solved using the inboard magnetometer, which provided measurements at a rate of 2.824 vectors per s (that is, simultaneously with every tenth outboard full vector) for two components, one parallel to the spin axis and one in the spin plane. Using the inboard and outboard magnetometer and magnetic test results before launch, a model magnetic field could be determined for the despin-motor stray field. This model field was subtracted from the observed field, leading to a substantial reduction of the stray field problem.

Because of its complexity and the lack of test results before launch, the camera's magnetic field contamination could not be removed in the same way. During the period discussed here, the camera operated from 20:03 UT on 13 March until a few seconds before closest approach (00:03 UT); that is, during part of the inbound leg. (All times given here are spacecraft event times.) The camera disturbance field consists of very slow variations, variations on an intermediate timescale of several spin periods caused by the rotation of the invar barrel of the camera, and short impulsive field perturbations up to ~ 3 nT in magnitude at a rate of 2 per spin period. Because of the precise location of the interval of camera operations, the relatively large magnitude of the ambient cometary field, and our good understanding of the influence of camera perturbations on the measured and averaged magnetic field vectors, our results and conclusions are only affected in a minor way by the camera stray field problem.

The instrument worked flawlessly throughout the Giotto mission, although some data were lost due to dust-impact-related problems around and after closest approach.

Overview. After the observations of the International Cometary Explorer (ICE) spacecraft at comet Giacobini-Zinner³, Giotto, Vega 1 and Vega 2, and the Japanese spacecraft Suisei provided the first measurements at a comet of intermediate gas production rate. Because of its very close fly-by, Giotto gave the first opportunity to study the innermost part of the interaction region.

The plasma interaction depends on the properties of the gas outflow from the comet and the characteristics of the incident magnetoplasma of the solar wind. The interplanetary medium was characterized by two magnetic sectors, and the current sheet was near the solar equatorial plane during the months before the encounter. During the 2-day interval centred on closest approach the magnetic polarity was predominantly outward, that is, positive, with some intervals of mixed polarity and a few hours of negative polarity. Thus the spacecraft was mostly located a little south of the current sheet separating the northern negative polarity from southern positive polarity. Because the

Fig. 2 Magnetic field magnitudes (B) based on 1-min average components from 18:00 UT on 13 March 1986 until 08:00 UT on 14 March. The interval of camera operations is indicated. Its influence on 1-min average vectors is estimated to be ≤ 0.6 nT.

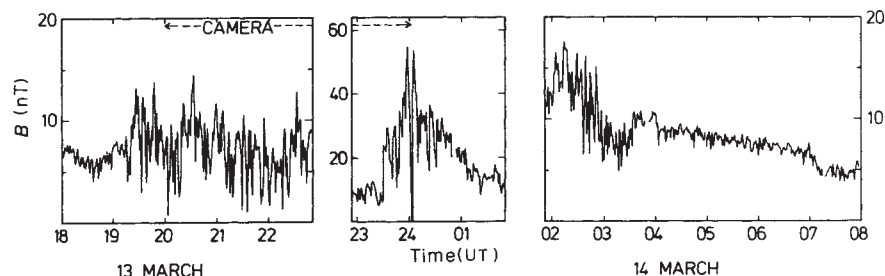
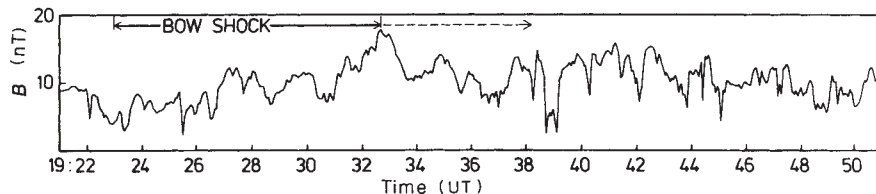


Fig. 3 Magnetic field magnitudes (B) based on spin-averaged components from 19:21 to 19:51 UT on 13 March, showing the inbound bow-shock crossing. The initial magnetic field increase is indicated by a solid line; the following variations (dashed line) may be part of the fine structure of the broad cometary shock, and/or due to non-uniform shock motion. The camera was not operating during this interval.



comet moved from north to south, it crossed the heliospheric current sheet from negative to positive polarity near the time of closest approach.

The first clear evidence for the continuous presence of magnetic field variations signalling the presence of the comet occurred at $\sim 16:00$ UT on 13 March, at a distance of 2×10^6 km from the comet. Other 'suspect' wave fields occurred long before this time. The wave fields of cometary origin displayed gradually increasing directional and magnitude variations as the comet was approached. The magnitude variations in particular are quite atypical for the solar wind. Typical periods of the dominant waves were 3–5 min; in addition, short, almost sinusoidal wave trains of much higher frequency were also observed. These waves can be attributed to instabilities generated by pick-up ions created by charge exchange and photoionization of cometary neutral particles.

Figure 1 shows the encounter geometry and the various interaction regions. The trajectory has been projected on the x - y plane of a Halley-centred solar ecliptic coordinate system, in which the x - and y -axes are parallel to the ecliptic plane, with x pointing towards the Sun and y antiparallel to the direction of planetary orbital motion. The spacecraft moves from south to north with respect to the x - y plane, crossing it shortly after the time of closest approach. The spacecraft relative speed of 68.4 km s^{-1} implies a spatial resolution of 2.4 km by the magnetometer experiment in the reference frame of the comet.

Figure 2 shows the variation of magnetic field magnitude (B) based on 1-min average vectors for the period from 18:00 UT on 13 March 1986 until 08:00 UT on 14 March. At $\sim 18:00$ UT the upstream waves reached amplitudes with maxima up to twice the magnitude of the minima. At $\sim 19:23$ UT, 1.15×10^6 km from the cometary nucleus, the magnitude began to increase, with superposed strong fluctuations, until at 19:33 a magnitude of 18 nT was reached. We consider this structure to be the first crossing of the cometary bow shock (see Figs 1 and 3).

The assumptions of average solar-wind conditions at 0.9 AU and a gas production rate of 4×10^{29} molecules s^{-1} according to Newburn and Reinhard⁴ had led us to predict the bow shock at $\sim 19:30$ UT (ref. 2) by scaling the ICE observations at comet Giacobini-Zinner³ with the help of some theoretical considerations⁵. A tentative estimate of the gas production rate Q from IUE observations now leads to an estimate of $Q = 5\text{--}6 \times 10^{29}$ molecules s^{-1} (C. Arpigny, personal communication) for the time of the Halley encounter.

After the bow-shock crossing, B decreased with strong superposed variations, until at $\sim 20:11$ UT a second structure began with characteristics similar to the first. It may be part of the fine structure of the bow shock, or represent a second bow-shock

crossing. Subsequently B remained at a lower level of ≤ 10 nT, with superposed variations which often reached minimum values of < 2 nT; the periods of the dominant variations were typically one to several minutes. We call this region the 'magnetosheath' region. Towards its inner boundary the directional variations subsided somewhat.

Following the magnetosheath, at 23:30 UT the magnetic field suddenly increased to values near 30 nT at a distance from the nucleus of 1.35×10^5 km. We call the region inside the magnetosheath the pile-up region. The large magnetic fields on the flanks of the interaction region can be attributed to the lengthening of the frozen-in field lines due to the draping process and to a lesser extent to plasma compression, both effects being described by Walén's theorem. The pile-up region also contained several deep dips in B lasting several minutes, which may be diamagnetic cavities associated with pressure enhancements, possibly related to the formation of tail rays⁶. The magnetic field reached a maximum at 23:59 UT; spin-averaged data with better resolution yield a maximum value of 57 nT (Fig. 4). Afterwards the magnitude started to decrease rapidly, to essentially zero when the magnetic 'cavity' was entered at 00:01:51 UT on 14 March 1986. This cavity is bounded by an ionopause or contact surface. Its existence had been predicted by theory⁷ and was expected by analogy with the case of Venus, where a null magnetic field region has been observed, and the ionopause has been extensively mapped⁸. A cavity has also been observed in association with the 'artificial comets' of the AMPTE mission⁹.

After ~ 2 min in the cavity the spacecraft entered the outbound pile-up region on the dawn side of the comet. At 00:05 UT, only ~ 1 min after leaving the cavity, the outbound maximum magnitude occurred (Fig. 4). It was even sharper than the inbound maximum and had a value of 65 nT in spin-averaged components. Giotto probably left the pile-up region at 01:07 UT, and entered the dawn-side magnetosheath. The boundary of the pile-up region was much less clearly defined outbound than inbound.

In contrast to the inbound pass, the evidence for an outbound bow shock was not very clear. In the time interval from 02:30 to $\sim 03:05$ UT a region of increased fluctuation amplitude could be discerned which may represent the outbound bow shock. This transition region was quickly followed by a gradually decreasing level of B -variations. These were superposed on a gradually decreasing half-hourly-averaged field magnitude starting at $\sim 04:00$ UT. In the half-hour averages the magnetic field direction displayed small gradual changes consistent with magnetic field line draping. There was no evidence for disturbances due to major changes in the interplanetary magnetic field. We suggest that the cometary bow shock may be a thick quasi-

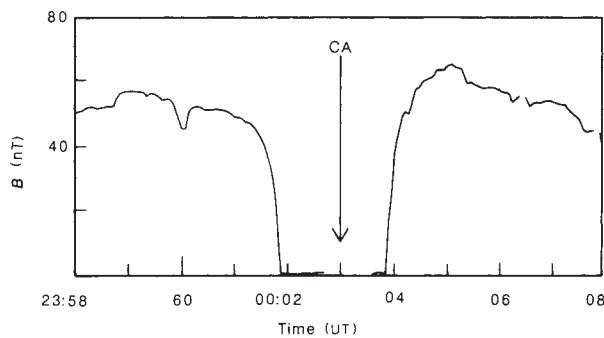


Fig. 4 Magnetic field magnitudes (B) based on spin-averaged components from 23:58 to 00:08 UT on 13/14 March, showing the inner pile-up region inbound and outbound and the magnetic cavity region. The curve is interrupted because of data gaps related to dust impacts near closest approach (CA). Although the camera operated until closest approach, its influence on the data shown is negligible.

parallel shock on the dawn side of the interaction region because the average magnetic field direction is close to the average normal to the discontinuity, as in the case of planetary bow shocks^{10,11}. The gradual monotonous decrease of averaged field magnitude lasted until $\sim 07:00$ UT. Upstream waves of cometary type could be seen continuously until $\sim 11:00$ UT; that is, to a distance of $\sim 2.7 \times 10^6$ km from the nucleus. Thus, the outbound pass gives the impression of a much more gradual decrease of magnetic field magnitude and fluctuation level than does the inbound pass.

Cometary bow shock. One of the interesting questions of cometary plasma physics has been the problem of the existence of a cometary bow shock separating a super-fast flow region (in the magnetohydrodynamic sense) at large distances from a sub-fast region near the comet. Following the proposal of a well-defined cometary bow shock¹², the possibilities of no bow shock or only a weak shock were also discussed¹³. In their first paper on the results of the ICE encounter at comet Giacobini-Zinner, Smith *et al.*³ joined other ICE investigators¹⁴ in using the term 'bow wave' to avoid the premature anticipation of the term bow shock before some refined studies had been made.

A final identification of the structure and nature of the disturbance starting at 19:23 UT on 13 March awaits a careful study involving plasma and magnetic field observations. We suggest, however, for reasons given below, that the observed structure can already be called a cometary bow shock.

In the case of a bow wave as a hydrodynamic feature describing, for example, the flow around a ship, we would expect the dominant length scales of the bow wave structure to be given by the scale of the obstacle in the near flow field and by the distance from the obstacle in the far field. Hence the thickness of the structure at large distances r should increase with r at the same observer-comet-Sun angles. In the alternative case of a well-defined bow shock, the shock thickness should depend only on the magnetoplasma characteristics just upstream and on the shock strength. This situation is expected at least for the quasi-perpendicular shock observed on Giotto's inbound pass.

Because the upstream plasma is already loaded with cometary ions and is accompanied by instability-driven turbulence of intermediate strength, we expect the shock structure to differ from quasi-perpendicular shocks in the quiet, proton-dominated solar wind. The shock thickness should be related to the gyroradii of the pick-up ions. Assuming partially thermalized OH^+ ions with a velocity of 200 km s^{-1} , and the measured magnetic field of 8 nT, we obtain a gyroradius of 4,400 km. The thickness of the cometary bow shock should be approximately the same for the inbound Giotto measurements at comet Halley

and the ICE measurements at comet Giacobini-Zinner (G-Z). Figure 3 shows the inbound shock transition as seen in the spin-averaged data. The Halley inbound shock is located at a distance $r = 1.15 \times 10^6$ km from the nucleus, and has a thickness along the Giotto trajectory, $\Delta r = 41,000$ km. The corresponding values observed during the ICE encounter with G-Z were $r = 1.27 \times 10^5$ km, $\Delta r = 31,000$ km. Neglecting the somewhat different angles between the relative velocity and the shock normals derived from the shock configuration in Fig. 1 (dashed curve), this comparison shows that in spite of a factor of 10 difference in radial distance the thicknesses are almost the same. The situation for the G-Z outbound bow-shock crossing is less clear because of interplanetary magnetoplasma variations during the ICE encounter; however, the peculiar ICE encounter geometry¹⁵ suggests a relatively large angle between the magnetic field and an average shock normal. We tentatively conclude that cometary bow shocks were observed on the Giotto inbound trajectory and at G-Z both inbound and outbound. The absence of a clear bow-shock signature on Giotto's outbound trajectory may be due to a quasi-parallel shock configuration.

Innermost interaction region. A particularly interesting part of the Giotto encounter with comet Halley was the passage through the innermost magnetoplasma regions not visited before by any other spacecraft. The most interesting measurements were made during a few minutes around the time of closest approach; in Fig. 4, spin-averaged magnitudes for this period are plotted on an expanded time scale. The magnetic field magnitude decreased monotonically with increasing steepness as the cavity region (with approximately zero magnetic field) was approached. The reverse sequence of events is seen outbound, where even greater field strengths were measured, perhaps due to the closer proximity to the sunward portion of the pile-up region where the magnetic field should attain its maximum value. Giotto entered the cavity at 00:01:51 UT on 14 March and left it ~ 2 min later, at 00:03:56 UT. At the time of writing, the times provided by the Giotto project have an unknown offset, resulting in an uncertainty of ~ 3 s. The time difference between entry and exit is 124.5 ± 0.1 s, corresponding to $8,513 \pm 7$ km along the trajectory; the boundary is very sharp. A full discussion of its detailed structure requires use of the maximum time-resolution of the observations (not shown here), and is deferred to a future publication.

The distances relative to the point of closest approach are more uncertain, due to timing uncertainties which should soon be (at least partly) resolved. The distance from entry to closest approach is $4,700 \pm 500$ km and from closest approach to exit $3,800 \pm 200$ km. The corresponding distances to the nucleus are 4,760 km and 3,840 km, respectively.

A comment of the significance of the zero-field is appropriate. Due to the spacecraft magnetic field contributions discussed above, the uncertainty in the magnetic field component parallel to the spin axis is relatively large. However, the 10 spin-averaged components B_x and B_y in the spin plane following entry into the cavity showed absolute values less than 0.2 and 0.3 nT, respectively. During the same time interval the B_z component, with spacecraft fields determined from interplanetary data before and after the fly-by, yielded 1.6 nT. This was taken as evidence for a zero magnetic field in the cavity and the need to correct for a remaining spacecraft magnetic field in the z direction.

Some preliminary estimates of the ionospheric plasma pressure inside the ionopause (within the cavity) can be made by assuming pressure balance between the magnetic field and the internal pressure as in the case of Venus¹⁶. A magnetic field pressure of $1.7 \times 10^{-8} \text{ dyn cm}^{-2}$ is obtained for 65 nT. Assuming a temperature of 1,000 K for ions and electrons, this magnetic pressure is balanced by an ionospheric plasma of density $6 \times 10^4 \text{ cm}^{-3}$. We note that the simple pressure balance used above is probably not a good assumption over a distance of 4,100 km between the outbound magnetic field maximum and the out-

bound ionopause. Frictional forces and the tensional part of the $\mathbf{j} \times \mathbf{B}$ force are probably important in the force integral over this distance.

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First results from the Giotto Radio-Science Experiment

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Doppler and ranging measurements, using the radio signals of the Giotto spacecraft and taken during the encounter with comet Halley, reveal a definite deceleration of the spacecraft due to drag in the cometary atmosphere. The total change in the radial velocity of the spacecraft was measured to be 16.7 cm s^{-1} , occurring over a time interval of $\sim 100 \text{ s}$ and corresponding to a shift in Doppler frequency of 4.7 Hz . Using this velocity change, estimates of the total cometary mass striking the spacecraft range from 0.1 to 1 g .

The scientific objectives of the Giotto Radio-Science Experiment (GRE) are to determine the columnar electron content of comet Halley's ionosphere and the mass fluence of the cometary atmosphere^{1,2}. For this purpose the radio signals from the Giotto spacecraft were used during the Halley encounter on 13-14 March 1986. The radio-science data were collected mainly at NASA's Deep Space Network 64-m tracking station DSS 43 at Tidbinbilla near Canberra, Australia. The measurements of cometary electron content and mass fluence will be inverted to derive the spatial distribution of the electron and mass (dust and gas) density within Halley's coma.

Giotto was equipped with redundant radio transponders capable of downlink transmission in the S-band (2.3 GHz) as well as in the X-band (8.4 GHz)¹; however, the Giotto project management decided for operational reasons to transmit only in the X-band during the Halley encounter. Due to this limitation the determination of the cometary electron content was badly

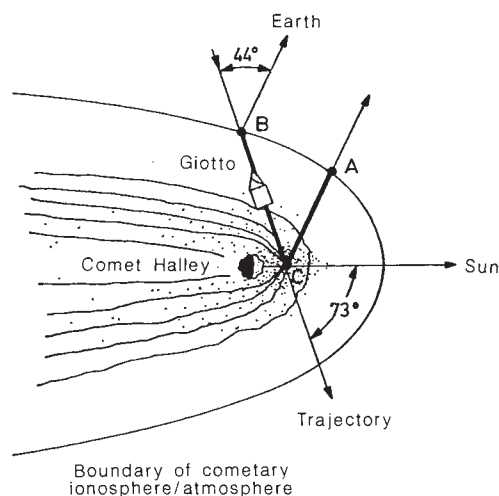


Fig. 1 The geometry of Giotto's Halley encounter on 13-14 March 1986. The cometary electron content represents the integrated electron density of Halley's ionosphere along the ray path C-A, the cometary mass fluence being accumulated from atmospheric drag along the trajectory C-B.

Table 1 Radio link budgets for GRE's prime station DSS 43 during Giotto-Halley encounter

	S-band uplink	S-band downlink	X-band downlink
Signal frequency (GHz)	2.117	2.299	8.429
TX power (dBm)	73	36.7	43.2
Ground antenna gain (dBi)	60.6	61.7	71.9
Propagation loss (dB)	-262.5	-263.2	-274.5
S/C antenna gain (dBi)	25.3	26.3	39
R.f. losses (dB)	-2.3	-1.9	-1.6
Signal level RX input (dBm)	-105.9	-140.4	-122
System noise temperature (dBi)	27.2	13.7	13.8
Boltzmann constant (dBm/HzK)	-198.6	-198.6	-198.6
Received S/N_0 (dBHz)	65.5	44.5	62.8
Modulation loss (dB)	0	-3.6	-8.2
PLL bandwidth (dBHz)	15.4	16.8	16.8
Required C/N (dB)	10	15	15
Margin (dB)	40.1	9.1	22.8

Coherent mode/ranging off: uplink unmodulated carrier, downlink telemetry plus Doppler. Noncoherent: column 3 only. Carrier recovery. Spacecraft elevation 30° . R.f. losses refer to circuitry, antenna pointing, atmosphere and polarization.

degraded. The GRE was the only experiment on Giotto capable of measuring the low-energy ($\approx 10 \text{ eV}$) bulk electron population of Halley's ionosphere and the total cometary mass flow impacting the spacecraft.

The geometry of the Halley encounter as relevant to GRE is shown in Fig. 1. Table 1 gives the radio link budgets representative for GRE data collection during pre-/post-encounter intervals (transponder in two-way, coherent mode) and during the Halley encounter (transponder in noncoherent mode).

Figure 2a shows the Doppler frequency shift measured around encounter with the highest possible rate of 10 samples per second. The post-encounter level of the Doppler shift has been normalized to the value of -4.7 Hz corresponding to a total change in radial velocity of -16.7 cm s^{-1} . This velocity change of the Giotto spacecraft, occurring over a time interval of $\sim 100 \text{ s}$, is interpreted as a deceleration induced by drag effects due to the atmosphere of comet Halley (momentum transfer). Corrections of those contributions to the Doppler shift resulting from the relative motions of spacecraft and Earth and from the

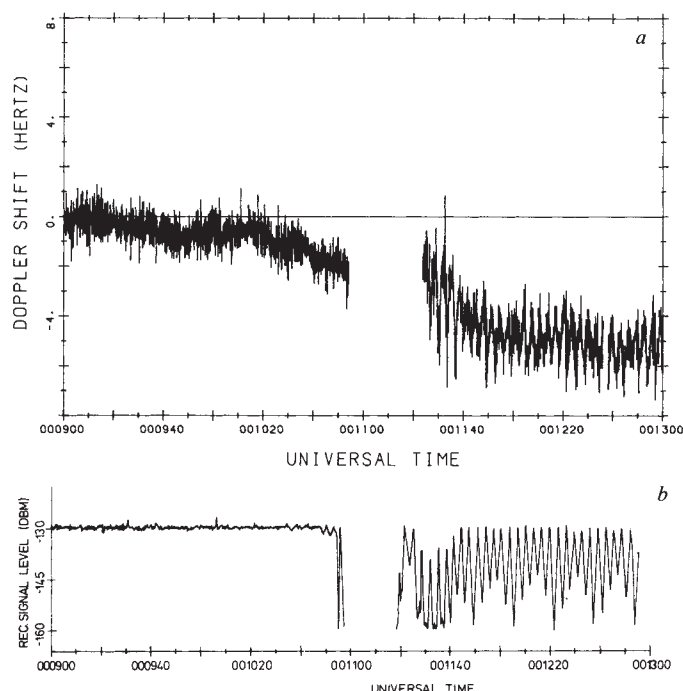


Fig. 2 Giotto radio metric data during the encounter with comet Halley on 14 March 1986 (DOY 73) from 00:09 to 00:13 UT (*a*, one-way Doppler; *b*, receiver AGC). The residual Doppler shift was not measured at DSS 43 during a 29-s gap from 00:10:55 to 00:11:23 UT, because the receiver was not locked on the Giotto X-band carrier signal. A second, less critical data gap of 2 s duration occurred starting at 00:12:36 UT.

oscillator drifts are already accounted for in Fig. 2*a*. Both of these effects are slowly varying on timescales relevant to the Halley encounter (tens of seconds). The specific encounter behaviour of the on-board oscillator (noncoherent mode), in particular its dependence on the ambient temperature, will be investigated in detail in future.

In a cooperative effort with CSIRO, simultaneous X-band Doppler measurements were taken during encounter using the 64-m antenna of the Radioastronomical Observatory at Parkes, Australia (about 400 km from Tidbinbilla). Figure 2*a* contains the phase information of the Giotto downlink signal (that is, the frequency, which is the time-derivative of the phase), and Fig. 2*b* represents the amplitude measured during cometary encounter at Parkes in terms of receiver automatic gain control (AGC: downlink carrier signal rectified and low-pass-filtered). As indicated the receiver was out of lock (signal below a threshold of about -158 dBm) within the time interval 00:10:57 to 00:11:18 UT. At Parkes the AGC time constant was as small as ~100 ms (significantly smaller than at Tidbinbilla). The effects of dust impact on Giotto's attitude can clearly be seen in Fig. 2 as post-encounter oscillations in the Doppler shift and AGC presumably caused by nutation of the spinning spacecraft's high-gain antenna axis.

The signature of the atmosphere of comet Halley on the one-way Doppler measurements during encounter (immediately before and after the data gap) is definitely confirmed by the two-way radio metric measurements of Doppler and range (coherent mode) before and after encounter (Fig. 3). Doppler velocity (Fig. 3*a*) and range (Fig. 3*b*) are expressed as residuals from those values predicted by orbit determination, where the radio metric data collected after the last manoeuvre but before encounter were found to be in good agreement with the predicted values (dashed lines). All these two-way data, which were taken after the last pre-encounter manoeuvre and before the first post-encounter manoeuvre, are not subject to the intrinsic

frequency instability of the on-board oscillator. The collection of the two-way radio metric data involved also the 64-m tracking stations DSS 14 (Goldstone, California) and DSS 63 (Madrid). The two-way data collected by the three 64-m NASA tracking stations for the Giotto spacecraft allow the Doppler velocity to be measured to an accuracy of approximately $\pm 0.05 \text{ cm s}^{-1}$ (corresponding to a frequency shift of $\pm 30 \text{ mHz}$). The errors in range are conservatively estimated to be less than $\pm 9 \text{ m}$ ($\pm 30 \text{ ns}$ in signal travel time).

Frequency spectra of the Giotto X-band carrier signal were measured in real-time and are shown in Fig. 4 for time intervals well before and during the Halley encounter (upper and lower curve, respectively). The measurement shown for encounter was taken shortly after the Doppler data gap (see Fig. 2*a*). Considerable degradation of the signal and a number of fine-scale spectral features can be seen from the encounter measurements (for example distortion of the spectral peak and width). These data used to derive the spectra of Fig. 4 were recorded at DSS 43 as waveform measurements in the time domain during intervals of ± 1 hour around encounter at a sampling frequency of 50 kHz. Since these waveform measurements were collected by using an open-loop receiver, the gap for the Doppler data (closed-loop receiver) is expected not to exist for the waveform data. A detailed analysis of these open-loop data will be performed in the time and frequency domain as well in order to associate the various kinds of signal distortion observed (such as signal attenuation, dispersion) with the spatial and temporal distribution of the cometary atmosphere and ionosphere, respectively.

In spite of the limitation on measuring Halley's electron content (see above), supplementary measurements were made during encounter to calibrate non-cometary plasma effects. The S-band downlink signal of Japan's spacecraft Sakigake (formerly MS-T5) to comet Halley was monitored for GRE at the 34-m station DSS 42 of the Tidbinbilla tracking site: thus the lines of sight to both Sakigake and Giotto became nearly identical¹. These Sakigake measurements will allow us to calibrate the electron content of the interplanetary plasma along the Giotto ray path. Very-high-frequency Faraday rotation measurements were also obtained for GRE at Tidbinbilla from a geostationary satellite (ETS-2) to provide a calibration mainly for the terrestrial

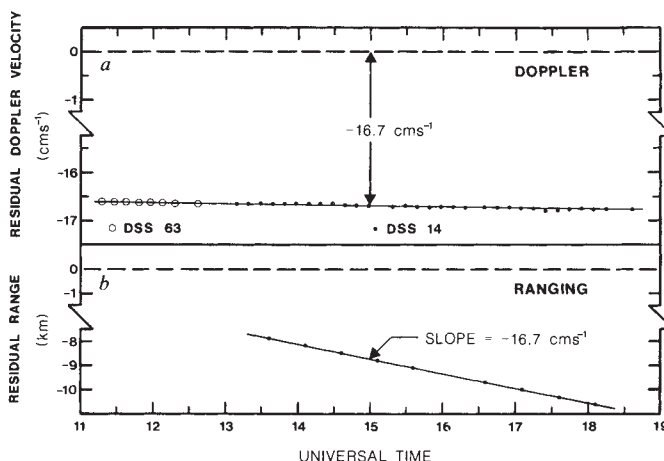


Fig. 3 Post-encounter radio metric measurements (two-way). The residual Doppler velocity (*a*) and residual range (*b*) are plotted for the two tracking passes at the NASA stations DSS 63 and DSS 14 on 14 March 1986. The radial velocity of the Giotto spacecraft was found to be 16.7 cm s^{-1} lower than predicted, a value that agrees with the slope (range rate) of the curve in *b*. The individual range points at DSS 14 indicate that the spacecraft was closer to Earth than predicted by values running from $\Delta R = -7.89 \text{ km}$ at 13:36 UT to $\Delta R = -10.61 \text{ km}$ at 18:06 UT. These range measurements yield a mean value of -16.7 cm s^{-1} for the total change in radial velocity.

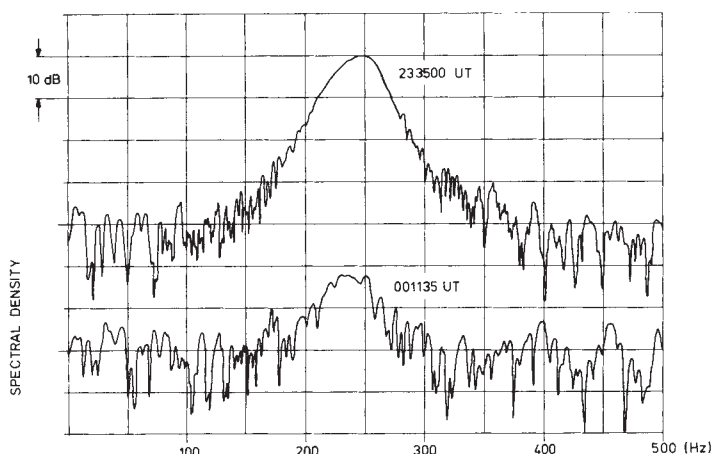


Fig. 4 Frequency spectra of the Giotto X-band carrier signal at times before and during the Halley encounter. The resolution bandwidth is 30 Hz over a frequency range of 500 Hz. It took a sweep time of 1.67 s to measure each spectrum. Both spectra are separated by an artificial offset of 30 dB.

ionosphere. A separation of the ionospheric electron content benefits from two aspects: during the Halley encounter the elevation angle of the line of sight to Giotto was as high as $\sim 70^\circ$ and the Earth's ionospheric electron content was found to vary slowly with time, with an average value of $\sim 2 \times 10^{17} \text{ m}^{-2}$. *In situ* plasma measurements⁵ made aboard Giotto indicate that the total electron content of comet Halley might have been even larger than the expected value of $\sim 3 \times 10^{16} \text{ m}^{-2}$. These supplementary measurements will be used in a later analysis aimed at extracting an estimate of Halley's electron content.

Taken altogether, the GRE data reveal a definite deceleration of the Giotto spacecraft as a result of drag effects of the cometary atmosphere. If we assume that the total momentum transfer occurred along the relative velocity vector between the spacecraft and the comet, then the preliminary value of 16.7 cm s^{-1} for the total change in radial velocity, derived from the two-way Doppler and range data of Giotto, translates into a total change of the spacecraft velocity of $16.7/\cos 44^\circ = 23.2 \text{ cm s}^{-1}$ (see Fig. 1). This change in velocity can be used to estimate the total mass of the cometary dust and gas striking the Giotto spacecraft¹⁻³. This estimate is subject to large uncertainties in the momentum multiplication factor⁴ arising from enhanced momentum transfer due to inelastic high-energy particle impacts. Knowing the mass of the spacecraft at encounter (573.7 kg) and the encounter velocity (68.37 km s^{-1}), the total cometary mass impacting the spacecraft was determined to lie in the range of 0.1 to 1 g.

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Dust jets in comet Halley observed by Giotto and from the ground

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A first map of discrete dust-emission sources on the nucleus of comet Halley was recently completed, based on a study of the morphology of 55 features (jets, spirals, envelopes and others) recognized and modelled on 34 digitally processed plates of the comet obtained during May and June of 1910. A brief progress report¹ and a preliminary version of the map² have already been published, while the detailed technical paper is in press³. In the process of fitting the dust features, an earlier determination⁴ of the nucleus spin vector in 1910—a necessary prerequisite for mapping the sources—was refined^{1,3}. Here we assess the relevance of our results based on the 1910 observations to the comet's current apparition, using data obtained by the Giotto spacecraft of the European Space Agency (ESA) and from ground-based observations. The problems involved are possible variations in the spin vector over the 76-yr period, survival of the dust sources, and the positions of the prime meridian at the two returns to the Sun. Evidence from ground-based and spacecraft imaging of dust jets is compared and the distribution of discrete dust sources on the nucleus surface studied.

Early 1986 results based on dust outbursts and stationary jets. Wide-field photographs taken shortly after the comet reappeared following its conjunction with the Sun in early February 1986 showed the structure of the dust tail to be extraordinarily complex (Fig. 1). Several nearly straight streamers extending in various directions to up to a few degrees from the nucleus are superimposed on the extremely broad 'background' tail, fanning out from the direction of the plasma tail through the north and terminating in a sharply edged anti-tail that points to the east-north-east. While the observed breadth of the tail and the anti-tail are not unexpected⁵, the day-to-day motions of the streamers indicate that these structures are discrete synchrones, or loci of



Fig. 1 Photograph of comet Halley exposed by K. S. Russell on 22 February 1986, with the UK 124-cm Schmidt telescope in Australia. The field is $\sim 2^\circ \times 2^\circ$. North is up, and east to the left. Photograph courtesy of the Royal Observatory, Edinburgh.

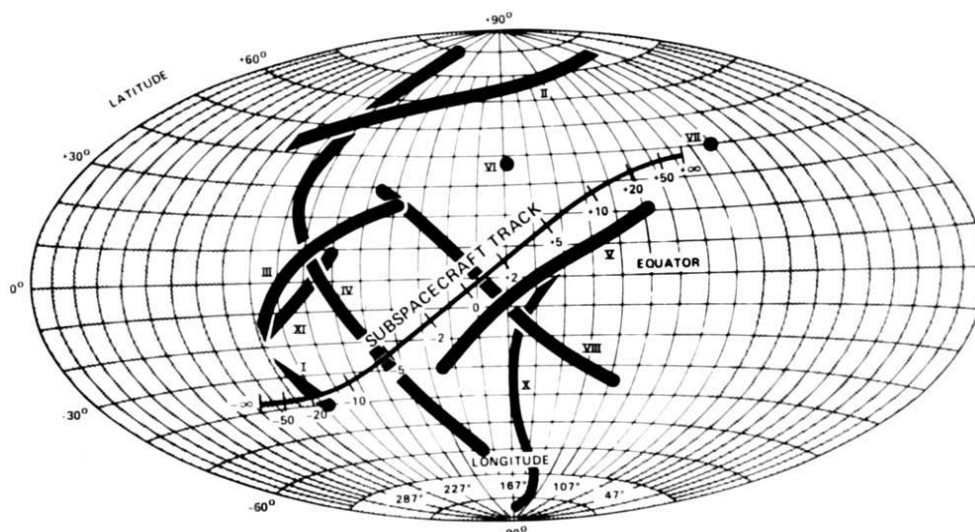
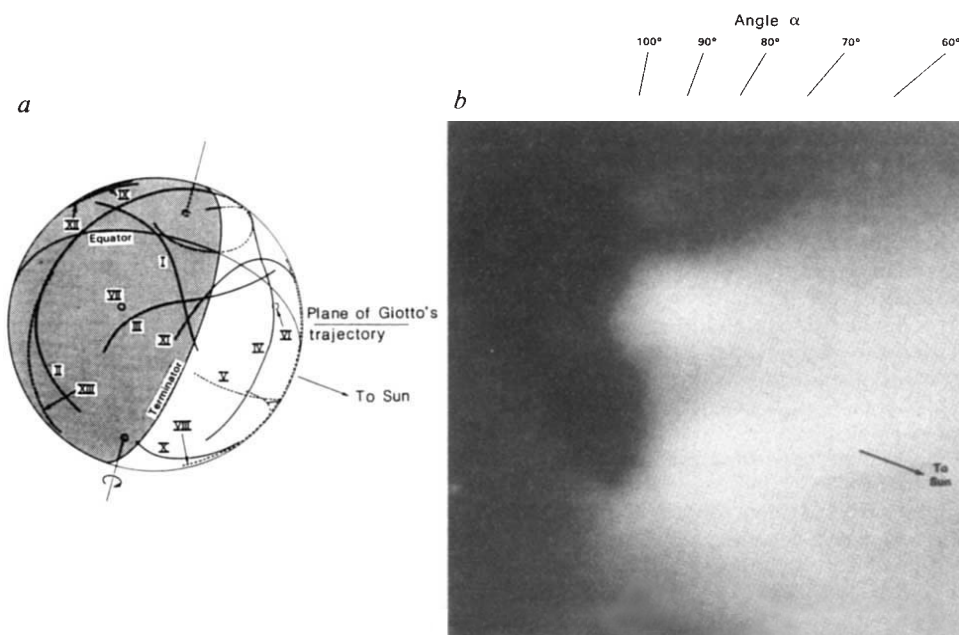


Fig. 2 The nominal path of the Giotto spacecraft projected onto the map of discrete dust sources on comet Halley's nucleus at the time of closest approach. The tick marks indicate the sub-spacecraft points at the various times reckoned (in s) from the instant of minimum separation. The points $-\infty$ and $+\infty$ define the path's radiant and anti-radiant. Shading represents the nucleus hemisphere not illuminated by the Sun. The point of closest approach on the actual trajectory was $\sim 25^\circ$ to the north-north-west of the plotted point (or south of the ecliptic), while there was little difference far from the comet.

Fig. 3 Comparison of the surface map of the discrete dust sources (a) from analysis of the 1910 photographs, projected onto a sphere viewed from the direction of the approaching Giotto spacecraft, with the image of the nucleus (b) taken by the camera aboard the spacecraft at a distance of 18,000 km from the object. Angle α is the projected angular distance from the direction to the Sun, counted anticlockwise. The 1910 north rotational pole of the comet has $\alpha = 95^\circ$. The 1910 linear sources (I–V and VIII–XIII) are represented by solid curves when on the near side of the spacecraft and by dotted curves when on the far side. The two point sources (VI and VII), represented by open circles, are both on the far side. The hemisphere not illuminated by the Sun is shaded. The image comes by courtesy of the Max-Planck-Institut für Aeronomie.



dust particles ejected in isolated outbursts, each probably lasting for no more than several hours.

Sekanina's analysis⁶ of these outbursts resulted in the identification of seven events between 29 January and 12 February, or 11 days before and 3 days after perihelion. The ejecta are believed to have originated from three discrete sources on the nucleus surface, in which case they recurred with a period of 52.5 ± 1.6 h or its multiples. Within the limits of uncertainty, this recurrence period coincides with the rotation period^{1,3} derived from the 1910 data. The times of the two sources that were responsible for the first five of the seven events are shifted in phase by almost exactly one-quarter of the recurrence period. Comparison with the map³ of the 1910 dust sources suggests a striking coincidence with the point-like regions VI and VII, whose longitude difference is indeed exactly 90° and which are known to have been active—mostly for only a few hours just before sunset—on more than one occasion in 1910. This very tentative identification provided the first (and the only pre-encounter) opportunity for estimating the longitude λ_0 of the prime meridian (defined as the sunward-facing meridian at the time of perihelion passage) in 1986. It was found to be $\lambda_0 = 236^\circ$ in the coordinate system of 1910, when λ_0 was 0° by definition.

Based on this tentative identification, the expected configuration of the 1910 dust-emission sources relative to the space-

craft's path was presented at the Giotto Project's Science Working Team meeting two days before the encounter (Fig. 2). The map shows that most of the dust sources are concentrated on the morning hemisphere, over which Giotto flew first. The map also shows that the spacecraft did not enter the sunlit hemisphere until 23 s before the time of closest approach.

Grün *et al.*⁷ have independently determined the rotation-axis position from their observations of prominent, nearly-stationary emission features pointing to the south on a few dates in November 1985. Their pole determination differs by $29\text{--}50^\circ$ from the solution that we obtained for 1910³, and would not fit the motions of dust features in that apparition. If confirmed by further modelling and/or from *in situ* images of the nucleus, the discrepancy could be explained only by nucleus precession.

Comparison with an image of the nucleus from Giotto. One of the images released by Giotto's Halley Multicolour Camera team shortly after the encounter shows details of the nucleus surface and emanating jets that warrant at least semi-quantitative comparison with our evidence based on the 1910 observations. Since the strongly flattened nucleus outline seen on this image (taken $\sim 18,000$ km before closest approach) provides no information on the third dimension of the object, and because much of the outline of the sunlit hemisphere is hidden by two prominent jets, the position of the spin axis can be estimated only in

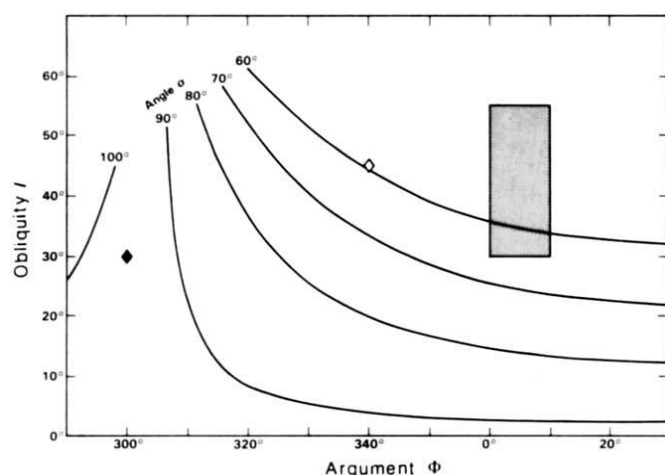


Fig. 4 Angle α (defined in Fig. 3) as a function of the two rotation-axis parameters Φ and I (see ref. 4 for their definitions). The initial⁴ and refined³ 1910 positions of the axis are shown as open and closed diamonds. The range of solutions suggested by Grün *et al.*⁷ is depicted by the shaded area.

general terms, and it certainly does not have to coincide with the object's projected minor axis.

The problem of the axial position is illustrated in Figs 3 and 4. Figure 3a is a map of the 1910 dust sources projected onto a sphere viewed from the spacecraft's direction, and Fig. 3b shows the nucleus image obtained by the Giotto camera. In Fig. 4 the loci of the spin-axis positions that yield equal angular distance from the Sun are represented by solid curves. Plots similar to Fig. 4 can be constructed for other points along the spacecraft's trajectory, for which images will be available in due time. A set of such plots may eventually provide tighter limits on the spin-axis orientation.

Because of the highly irregular shape of the nucleus, comparison between the image and the map in Fig. 3 is very difficult. Qualitatively, however, there appears to be good agreement between the position of the site of the major jet pointing to the right and the general area of intersection of sources III, IV and XI; in particular, this jet seems to expand in the general direction of the approaching spacecraft, as it should if the vent area from which it emanates is to be associated with the region delineated by the three linear sources. Similarly, there is a satisfactory correspondence between the site of the major jet pointing to the lower right and the global region where sources V, VIII and X come close to one another, if the jet comes from the far side of the nucleus, or between its site and the area of source IV that is close to the south end of source V, if the jet comes from the near side. Furthermore, the site of one of the two minor jets, which is apparently directed along the line of sight towards the spacecraft, could be related to the area where sources I, III and XI cluster together; this region should be very near the morning terminator at the time of encounter and the relative inconspicuousness of this jet may be due to the fact that its source is just being activated. Finally, the minor jet that points to the upper right in Fig. 3b is believed to have emanated from the area where sources II and IV are seen to meet on the map. For each of the four jets we definitely find a satisfactory correspondence between the sites of their emission and the tentatively assigned dust sources in relation to the spacecraft's plane of trajectory, that is, in the dimension in which distances can be perceived from the image relatively easily.

Subject to future inspection of a larger number of images, we tentatively conclude: (1) that the regions at which the various mapped sources meet are candidates for major emission vents or sites of principal activity; (2) that the linear sources we recently introduced³ are partly boundaries of these major dust-emission areas and partly lines connecting some secondary vents

that are only occasionally active (explaining the apparent tendency of linear sources to intersect one another); and (3) that in general much of the sunlit hemisphere at the time of encounter may indeed be a "vast reservoir of dust which is highly structured horizontally and probably also vertically" as we stated recently³ in reference to the hemisphere that in Fig. 2 essentially occupies the sunlit side of the nucleus at the time of Giotto's closest approach to the comet.

Ground-based imaging of high resolution in 1986. Large numbers of 1985–86 high-resolution images of the comet have begun to emerge, thanks largely to the cooperative efforts of the members of the International Halley Watch's Near Nucleus Studies Network. Qualitatively, these observations indicate a remarkable similarity between the general patterns of dust-feature evolution in 1910 and 1986. All the types of structure seen on the old plates—such as spirals, halos and straight anti-sunward jets—are clearly recognized on the new images.

Figure 5 presents a small sample of charge-coupled device (CCD) images showing some of these features and their slow evolution with time. The observations were made with the 152-cm reflector at the Boyden Station Observatory, University of the Orange Free State, Bloemfontein, South Africa, and the 223-cm reflector of the University of Hawaii on Mauna Kea. The images shown are from the period 27 February–15 March 1986 and include two pairs of pictures taken, respectively, shortly after the Vega 1 and Giotto encounters with the comet. The images were digitally processed using the radial/rotational shift algorithm proposed and applied earlier to the 1910 photographs⁸.

Early modelling of dust features in 1986. Our model of dust-coma features has been described elsewhere^{3,4}. Here we recall that

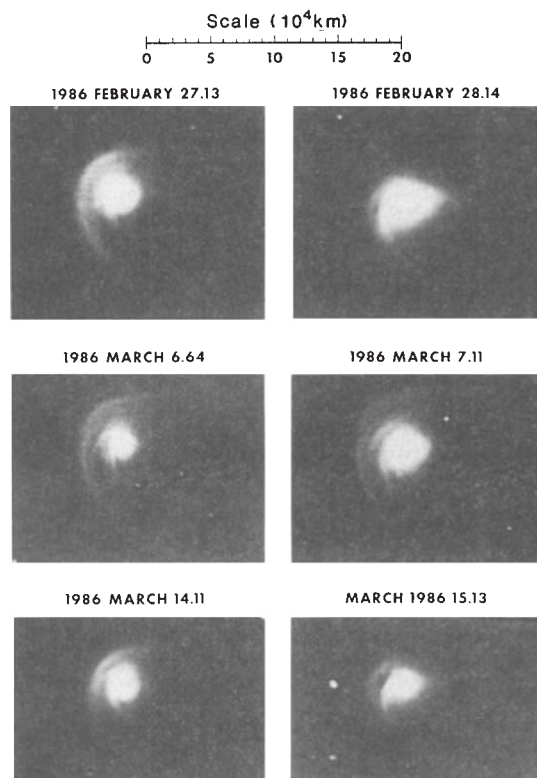
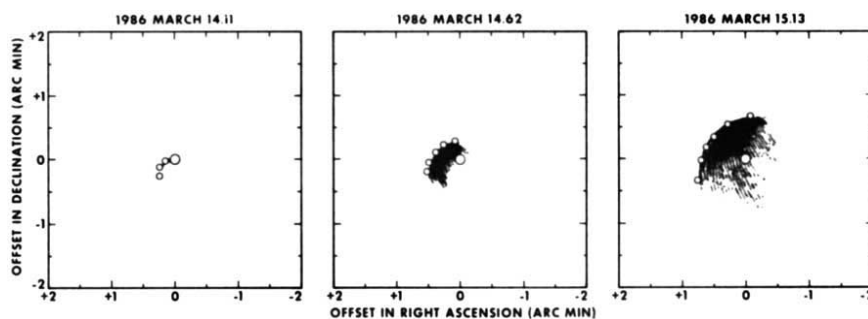


Fig. 5 Digitally processed images of the dust coma of comet Halley on 27–28 February, 6–7 March and 14–15 March 1986. The image on 6 March was obtained by A. Storrs and D. Cruikshank with the University of Hawaii's 223-cm reflector and reduced by N. Lark and M. Buie. The other images were obtained by S.M.L., S. Tapia and M. Senay with the Boyden Observatory's 152-cm reflector. North is up, east to the left. The images have a common linear scale at the comet, as indicated. The times of observation are given in UT.

Fig. 6 Comparison between the measured boundaries of dust features identified on three CCD images obtained on 14–15 March and the modelled continuous dust emission from source 1986-A. The observation on 14.62 March was made by A. Storrs and D. Cruikshank with the University of Hawaii's 223-cm reflector and reduced by N. Lark and M. Buie. For the observations on 14.11 and 15.13 March, see Fig. 5. The dust emission was assumed to start 3 h before local noon and to continue until sunset. Offsets in right ascension and declination are calculated from the nucleus (large circle). A perfect match between model and measurement is achieved when the measured points (small circles) on a feature's boundary lie precisely on the envelope to the dust-particle loci (curves). The times of observation are given in UT.



detection of dust sources is limited by the fact that the technique used provides calculated outlines and their expansion rate only for the outer boundary of each major feature. If this feature is in fact a composite of a number of smaller features, the mapped linear source corresponds to a line connecting the easternmost points of activity, from which the emission proceeds first.

Although there is no indication from Giotto's images of the cometary nucleus that the discrete sources of dust are preferentially extended in any particular direction, the concept of linear sources^{2,3} has proved useful in delineating the eastern limits of dust emission from any confined cluster of isolated vents (or systems of vents) active at any particular rotation. With this qualification in mind, we have applied this approach to a few recent high-resolution images of Halley.

Using the comet's refined spin-vector parameters for 1910^{1,3}, we have now identified three sources of dust on the processed images measured, and have tentatively called them 1986-A, 1986-B and 1986-C, the first two accounting for features observed on 14–15 March. As an example, Fig. 6 shows the quality of fit for 1986-A. The southern part of 1986-A is likely to be identical with the vent that is seen on the Giotto image in Fig. 3 to issue the bright jet to the lower right. This vent is also likely to have been the source of the large particle(s) that hit the Giotto spacecraft shortly before closest approach, causing it to wobble. Source 1986-B is probably identical with the 'point' source VI, known to have been active on several occasions in May and June of 1910³. On the Giotto image this vent is on the far side and any emission from it would be obscured by the major jet that points to the right. The ground-based observations show no evidence of this latter jet, unless its eastern boundary (hidden on the spacecraft image) coincides with the mid-northern por-

tion of 1986-A. If it does not, this feature would be confined to the inside of the boundaries of the other emission, explaining its apparent absence on the ground-based images. Although 1986-A is not identical with any of the 1910 sources detected, it intersects sources V and VIII and is almost certainly related to the major emission centre (bounded by sources V, VIII and X) that was active during the previous apparition (Fig. 7). The required correction of 10–20° in λ_0 is within the current limits of uncertainty. The third source, 1986-C, is responsible for an expanding envelope seen on 27–28 February and seems to be related to source XIII observed in 1910.

The velocities of ejection are found to vary widely between sources. This fact is important for interpreting the *in situ* dust measurements in view of the relatively long flight times needed for the particles to reach the detectors aboard the spacecraft.

Conclusions. Our working hypothesis of short-lived intermittent discrete sources of dust on the nucleus surface of comet Halley has been spectacularly confirmed by the close-up imaging with the Giotto camera. Our conclusion^{3,4}, from analysis of ground-based observations, that there is no jet emission from the dark side of the nucleus has also been confirmed.

A study of outbursts from the synchronic structure of the dust tail and their recognized periodicity⁶ turned out to be a major step in our efforts to determine the prime meridian for the 1986 apparition, making possible a direct comparison between the 1910 nucleus map and the 1986 images taken from the spacecraft as soon as the latter became available. Very recent modelling of several 1986 jets has led to results generally consistent with the initial value of λ_0 , even though the uncertainty involved may be as much as a few tens of degrees.

It is exciting to find that the dust-jet evolution can be described consistently by combining the spacecraft and ground-based observations. Work remains to be done on the nature of the discrete sources of dust, on the relationship between the major vents apparent on the Giotto images and the clustering of the linear sources inferred from ground-based observations, and on the interpretation of the linear sources in the light of the results from *in situ* imaging.

Further unresolved problems include the interrelationship between the shape of the nucleus, the current position and stability of the spin axis, the coordinate system and the longitude of the prime meridian on the irregularly shaped, potentially wobbling object, and the comet's brightness variations at large heliocentric distance. The brightness amplitude corresponding to a maximum-to-minimum cross-sectional area ratio of ~5 and a weakly pronounced periodicity of 52 h (ref. 9) (which is compatible with independent spin-rate determinations) suggest, in the presence of a strongly non-spherical nucleus, a greater role for rotational-related effects on the light curve than was generally accepted before the encounters.

The continuing intensive modelling of the dust features—combined with further information from the flight projects—should lead to a refined determination of the rotation-axis position (or its variations with time) in 1986, thereby addressing the

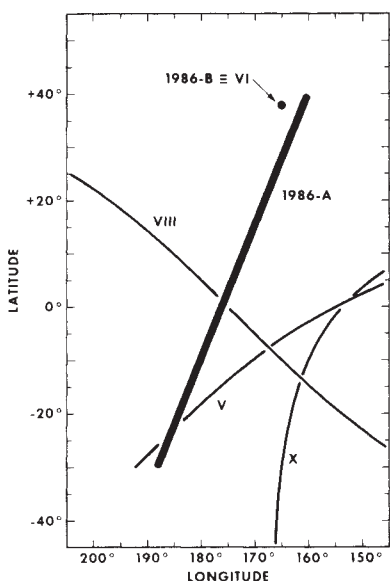


Fig. 7 Locations of sources 1986-A and 1986-B on the nucleus surface of comet Halley relative to their nearby 1910 sources for $\lambda_0 = 236^\circ$ in 1986.

problem of nucleus precession. Hopefully, the present tentative conclusions will stimulate more sophisticated studies of the comet's surface morphology and the pattern of dust emission from the nucleus.

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IUE observations of comet Halley during the Vega and Giotto encounters

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The observations of comet Halley from the International Ultraviolet Explorer (IUE) satellite from 9 to 16 March 1986 allow a comprehensive study of gas and dust production by the comet in the week during which the fleet of six spacecraft from four space agencies encountered the comet. The gaseous output of the nucleus was found to vary over timescales of the order of one or two hours. The Vega 2 probe crossed Halley's coma at the time of, or shortly after, the onset of a strong outburst. The Giotto spacecraft performed its measurements while the cometary nucleus was near a minimum of activity. The ultraviolet spectrum of comet Halley differs from that of other comets observed by the IUE satellite in that the continuum emission is very strong relative to the gaseous emissions, and the CO_2^+ violet bands, if present, are weak. The rate of water production was estimated to be 5.6×10^{29} and 5.2×10^{29} molecules per second at the time of the Vega 2 and Giotto encounters, respectively, while atomic carbon was a few per cent and CO ~10-20% of these values.

IUE has been used over the past few years to record the ultraviolet spectrum of nearly 25 comets, characterizing their ultraviolet spectra and performing comparative studies¹⁻³. Since⁴ 1 April 1985, the IUE satellite has monitored the ultraviolet spectrum of comet Halley at regular time intervals. The results presented here were obtained when the comet was at a heliocen-

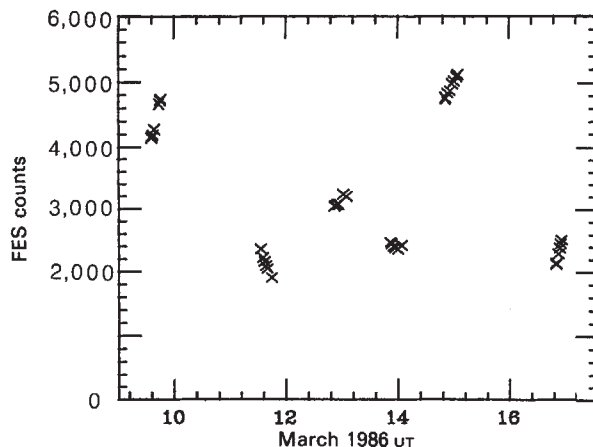


Fig. 1 Fine error sensor count rates. This parameter, strongly correlated with the activity level of the cometary nucleus, exhibits variations over timescales of the order of 1-2 h. Note that visible brightness extrema differ by a factor of 2.5.

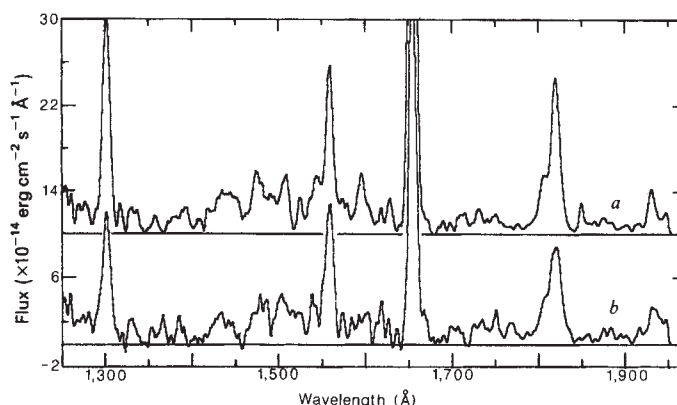


Fig. 2 Low-resolution spectra recorded with the SWP camera at the time of the Vega 2 (a, SWP 27884) and Giotto (b, SWP 27914) spacecraft encounters with comet Halley.

tric distance of ~0.9 AU and a geocentric distance of ~1.0 AU (mean values over the 9-16 March period). All brightnesses were measured with a 10×20 arc s aperture. Tracking of the comet was achieved by maintaining the centre of brightness of the coma at the centre of the spectrograph slit. Pointing accuracies were of the order of 1 arc s during short exposures and 2-3 arc s during longer ones.

The fine error sensor (FES) of IUE was used to find the centre of brightness of the coma and to monitor the activity of the comet. The FES camera provides a measure of the cometary brightness in visible light in an area of approximately 12×12 arc s (underlap mode). Most of the signal is due to C_2 and continuum emissions. The FES count rates (Fig. 1) indicate that the number of counts varies over timescales of the order of one or two hours. Since the lifetime of the C_2 radical parent is of the order of 5 hours⁵, short-term variations of the nucleus gaseous output should not affect the FES count rate. The fairly good correlation between FES count rate and continuum fluxes recorded in the gas-emission-free 2,910-3,010 Å bandpass provides an additional indication that most of the observed emissions are due to coma grains. Examination of Fig. 1 thus indicates that the Vega 2 encounter occurred at, or shortly after, the beginning of a strong outburst. At the Giotto encounter, the nucleus was near a minimum of activity.

About 20 low-resolution spectra and a few high-resolution spectra were recorded in 6 observing sessions of 4-8 h, during

* Guest observer with the IUE satellite.

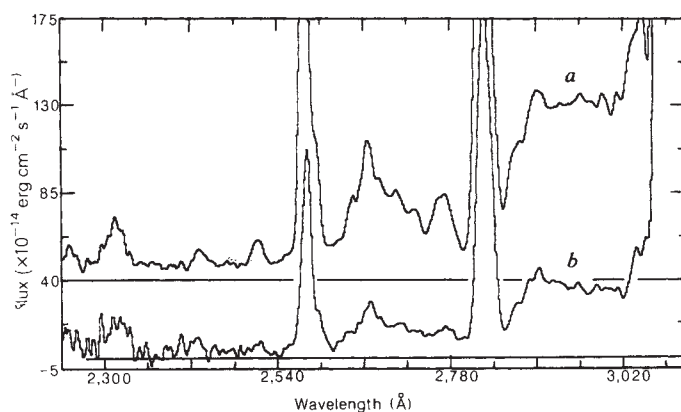


Fig. 3 Low-resolution spectra recorded with the LWP camera at the time of the Vega 2 (a, LWP 7766) and Giotto (b, LWP 7789) spacecraft encounters with comet Halley.

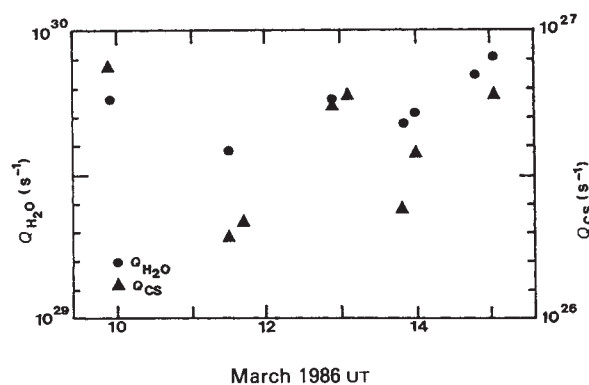


Fig. 4 OH (Q_{H_2O}) and CS (Q_{CS}) production rates between 9.6 and 15.1 March 1986. Note the very large fluctuations of the CS production.

which both SWP (short-wavelength primary) and LWP (long-wavelength primary) cameras were used. Very large variations were observed between spectra, particularly when the nucleus was 'active'. The entire spectrum of the comet during the Vega 2 and Giotto encounters is shown in Figs 2 and 3. The emissions were identified in Fig. 2, recorded with the SWP camera, due to O I (1,304 Å), CO (fourth positive system in the 1,410–1,640-Å interval), C I (1,561-Å, 1,657-Å and 1,931-Å emissions) and S I (1,813 Å). The C II (1,335 Å) line may also be present. The H I Lyman- α emission is not shown because it is saturated (not because the H I coma is optically thick). In Fig. 3, the emissions of the C₂ ($\Delta v = 0$), CS (1-0, 0-0, 1-1 and 0-1 bands) and OH (1-0, 0-0 and 1-1 bands) radicals can be identified above a strong continuum spread over the 2,200–3,400-Å interval. Longwards of the OH (1-1) band, a few features

are observed, among which the NH emission is easily identified. Figure 3b, for which the S/N ratio is higher than that in Fig. 3a, shows that the continuum is almost the colour of the Sun. This indicates that particles smaller than 0.1 μ m do not contribute significantly to the recorded signal. Note that the C I 1,931-Å line in Fig. 2b lies on top of the continuum emission, never observed in the blue part of the spectrum.

The most striking result obtained from examination of Fig. 3 is the weakness of the CO₂⁺ ultraviolet double-band signature, easily recorded in previous IUE observations of less gassy and less dusty comets^{6,7}. These observations do not indicate whether this weakness is due to a strong CO₂ deficiency in comet Halley or to an inhibition of emission (for example, loss of the ions through an efficient electron recombination process or charge-exchange reactions). Note that the ion signature, the presence of which is suspected in Fig. 3a (near 2,900 Å), recorded when the density of the various coma species was low, may be masked by the strong continuum emission. Comparison of these observations with those of comet Austin (which has a very strong CO₂⁺ signature⁷) suggests that the first of the above assumptions is the more likely.

The C₂ Mulliken bands are observed in Fig. 3 by their $\Delta v = 0$ sequence. The width of the emission indicates that the rotational distribution of the lines corresponds to a rotational temperature of a few hundred degrees. The general appearance of the band is very similar to that of the R-branch of the CN violet band. The electron temperature of the Mulliken bands, assessed by the absence of bands other than those recorded near 2,313 Å, is very different from that of the Swan bands, probably because of the efficient cooling of the C₂ singlet radicals via emission of the Philipps bands in the near-infrared.

Table 1 shows the fluxes recorded with the LWP camera. The fluctuations of the continuum and CS emissions have a larger amplitude than those of the OH emissions, which is consistent with the shorter dust cloud renewal time (typically a few hours) and the CS parent lifetime constants. The less marked variation of the C₂ emission compared with that of CS indicates that the lifetime of the C₂ singlet radicals is of the order of 10⁴ s. This is consistent with the possibility that the C₂ (singlet) radicals originate from the dissociation of an unidentified molecule which differs from the C₂ (triplet) parent and has a dissociative lifetime of $\sim 10^4$ s, as well as with the possibility that the singlet radicals are produced via the radiative decay of the triplet radicals.

The OH and CS brightness can be converted into H₂O and CS production rates by standard procedures (vectorial model for the atmospheric model⁸; OH and CS fluorescence efficiencies are given by Schleicher and A'Hearn⁹ and Feldman *et al.*¹⁰, respectively). The results are shown in Fig. 4, which indicates

Table 1 Brightness recorded with the LWP camera

Date	OH(0-0)	OH(1-0)	Continuum*	CS(0-0)	C ₂
9 March	900 (14:21)	20.9 (14:21)	33.1 (14:21)	10.8 (14:21)	—
	—	—	35.8 (18:05)	—	2.3 (18:05)
11 March	545† (13:20)	12.7 (13:20)	10.7 (13:20)	2.95 (13:20)	—
	—	—	12.5 (18:00)	3.50 (18:00)	1.0 (18:00)
12 March	730 (20:53)	15.8 (20:53)	24.3 (20:53)	8.70 (20:53)	—
13 March	—	—	22.2 (00:30)	9.75 (00:30)	1.6 (00:30)
	585 (21:05)	13.1 (21:05)	15.2 (21:05)	3.90 (21:05)	—
	—	—	12.6 (23:00)	4.80 (23:00)	1.40 (23:00)
14 March	630† (00:01)	14.7 (00:01)	14.4 (00:01)	6.00 (00:01)	1.75 (00:01)
	745 (20:32)	18.1 (20:32)	34.6 (20:32)	—	—
15 March	930† (01:12)	21.6 (01:12)	37.6 (01:12)	9.80 (01:12)	2.10 (01:12)

Brightnesses were integrated over the 10×20.3 arcs slit centred on the nucleus, the hour (middle of exposure, UT) at which observations were performed is indicated under each value (expressed in kilorayleighs).

* 2,910–3,010 Å.

† Assuming a ratio of 43 between the 0-0 and 1-0 band brightnesses, average value measured during our observing period.

† 2,910–3,010 Å.

clearly that the CS production variations quite closely mimic those of the dust emission. The less marked variation of the OH production rate indicates that the outburst duration is short compared with the OH cloud renewal time constant of 1–2 days at 0.9 AU, in good agreement with the information provided by the FES camera.

Table 2 gives the brightness variations of the O I, CO, C I and S I emissions. The CO emission shows two maxima around 9.9 March and 13.8 March 1986, at the same time that the CS production reaches its peak values. Such behaviour might be expected from a species that is released directly from the nucleus. Using the fluorescence efficiencies indicated by Feldman¹¹, we deduced that the CO production during our observations was

Table 2 Brightnesses recorded with the SWP camera

Date	9 March	11 March	12 March	13 March	14 March
Hour*	14:38	13:31	21:02	21:16	00:49
Exposure time (min)	45	120	60	70	41
O I	400	335	280	270	270
CO ⁺	1,250	850	1,220	920	880
C I (1,561 Å)†	315	320	245	370	250
C I (1,657 Å)	1,220	820	815	840	785
S I	570	370	440	425	410
C I (1,931 Å)	130	75	75	50	80

Brightnesses were integrated over the 10×20.3 arc s slit centred on the nucleus (expressed in rayleighs).

* Beginning of the exposure.

† All bands in the 1,410–1,635-Å interval.

‡ A somewhat uncertain value due to the blend with the (2–2) band of CO.

~150 times that of CS, or $5\text{--}10 \times 10^{28}$ molecules s^{-1} . These values are only rough estimates and could be in error by a factor of 2–3. The sulphur triplet has a very abnormal shape, probably due to a strong optical depth effect¹². A high-resolution spectrum allowed us to measure the wavelength of the various lines of the triplet unambiguously, and to conclude that the emission near 1,810 Å is due to the $^3\text{P}\text{--}^3\text{S}$ transition of atomic sulphur. The variations of the C I emissions cannot be discussed without considering in detail the strong Swings effect (a Doppler effect due to the heliocentric velocity of the comet) which affects these lines. A comparison with comet Bradfield (1979 X)¹⁰ indicates that the abundance of carbon atoms in comet Halley is at most a few per cent that of water and that carbon atoms probably result from the dissociation of minor species, a conclusion already reached by Festou¹³ for comets thought to be fairly old. Unless the weakness of the C I emissions is subsequently found to be due to a strong Swings effect, it would be interesting to know whether or not a large C I abundance is directly related to a large abundance of CO₂⁺ ions.

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Post-perihelion imaging of comet Halley at ESO

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The near-nucleus and large-scale activity of comet Halley has been monitored at the ESO La Silla Observatory since mid-February 1986. During an 8-week period with excellent observing conditions, images obtained with three telescopes documented the post-perihelion behaviour on a daily basis. We describe the instruments and procedures and provisionally summarize the major structures and events that were seen at the time of closest approach of the various spacecraft, between 5 March and 14 March 1986.

The earliest, optical observations of comet Halley after perihelion were made on 09:40 15 February 1986 UT with the ESO 40-cm double astrograph (GPO)¹, as part of an astrometry programme in support of the navigation of the spacecraft en route to the comet. On this date, and daily thereafter until 6 March, several short (that is, 5-, 20- and 60-s) exposures were made on red-sensitive plates (098-04+RG630; 630–700 nm; almost exclusively sunlight reflected from dust). Of 46 astrometric positions, which were transmitted with minimum delay (≤ 5 h) to the various spacecraft centres, 42 were of acceptable quality, constituting ~25% of a total of 162 astrometric positions which became available before 12 March. The GPO r.m.s. values, based on a post-encounter orbit, are (right ascension, declination) = (0.96, 1.06 arc s); T. Morley, personal communication.

After 17 February, when the comet could be observed more than 2° above the local horizon, it became clear that the red astrometric exposures, when supplemented with a few longer ones, would provide an efficient method of near-nucleus dust monitoring. For this purpose, daily 3- and 10-min red and 5-min blue (unfiltered Ila-O; 300–480 nm; mainly CN and CO⁺) plates were added in late February. As a result of excellent seeing throughout the observing period, the spatial resolution of most of the GPO plates is 1–1.5 arc s (plate scale = 50.5 arc s mm⁻¹), corresponding to ~1,000 km (projected) by early March.

Commencing on 18 February, the ESO wide-field CCD (charge-coupled device) camera (WFCC) has been used for observations of large-scale phenomena in Halley's tail. This instrument consists of an equatorially mounted RCA SID 503 EX CCD (640 × 1,024 pixels) behind a Canon f/2.8 100-mm objective; the field is 5.5 × 9° (1 pixel = 31 arc s). The detector is cooled by liquid nitrogen. Standard 1.5-inch IHW (International Halley Watch) comet filters were available. The initial broad-band observations (500–1,100 nm) demonstrated the complex dust tail system² and allowed a calculation of outburst epochs near perihelion³. When the moonlight started to interfere in late February, observations were begun in several of the interference filters. As comet Halley moved higher in the sky, more and more observing time became available each morning and a unique series of very deep exposures were made, in particular through the 426-nm (CO⁺) and 702-nm (H₂O⁺) filters.

Each frame was exposed for 10–15 min. To cover the full extent of the tail as well as possible, additional off-set exposures were made on several dates. In addition to the importance of the large dynamic range, the CCD technique in principle allows the removal of background objects by subtraction of later exposures of the same field, but without the comet. This is particularly useful for images obtained while the comet was near the galactic plane (late March–early April).

Owing to hardware limitations, observations of comet Halley with the ESO 1-m Schmidt telescope could only start when the comet was more than 10° above the horizon in late February. During the Moon period, short red exposures were made, but from 8 March onwards, one deep blue (IIa-O+GG385; 385–480 nm; CN and CO^+) and one red (IIIa-F+RG630; 630–700 nm; dust) plate were obtained each morning. These plates have a scale of $67.5 \text{ arc s mm}^{-1}$ and show a wealth of details in the innermost 4° of the ion and dust tails.

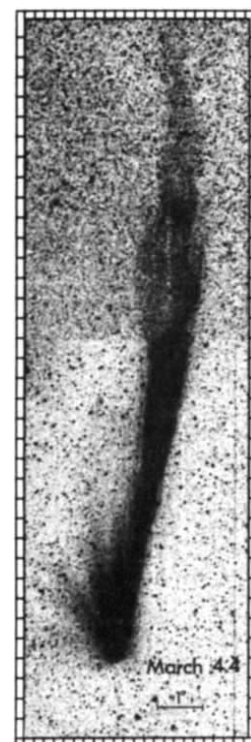
It is intended that the above observations will continue until mid-May 1986 or longer. They have been greatly favoured by optimal observing conditions (by 14 April, only two nights had been lost) and the resulting uniform material will provide a unique record of comet Halley's post-perihelion activity. Calibration will be made by stars in the field (GPO), selected standard stars (WFCC) and by Eta spectrogrammes (Schmidt). The reduction will involve numerous night-to-night transfers and will require a major effort. Some preliminary results have been published in IAU circulars⁴.

To provide a record of events at the time of the closest approach of the spacecraft, the corresponding plates and frames were inspected. For each date in the interval 5–14 March, a brief description of events is given below, based on the near-nucleus dust images from the GPO, the Schmidt high-resolution dust and ion inner-tail structure, and the WFCC CO^+ large-scale structure. Position angles (p.a.) are given in degrees, from north over east, and angular measures (d) in the tail are also given in degrees (note that we have not attempted to calculate the corresponding distances, as the exact projection angles are unknown). The GPO and Schmidt epochs are 08:30–09:30 UT; the WFCC epochs are indicated.

5 March. Central condensation (CC) was relatively strong and elongated ($5 \times 8 \text{ arc s}$; this and the following CC sizes were measured from 20-s red exposures) at p.a. = 135° . A jet was seen at p.a. 180° . The inner coma was very diffuse with weakly defined boundaries at 12 and 20 arc s, north-east of CC. The total coma diameter (measured across CC, perpendicular to the main tail direction on a 10-min red exposure) was 3.5 arc min. Using the WFCC (08:00–09:35 UT), the main tail was seen to bifurcate at $d = 1.2$, p.a. = 262° ; the bifurcation was also visible on 4 March (Fig. 1).

6 March. CC was round (diameter 3 arc s) and much weaker than on 5 March. There was an umbrella-shaped halo, sym-

Fig. 1 Composite WFCC image (at half-resolution) of comet Halley's CO^+ (426 nm) tail on 4.4 March. Pixels are indicated; 1 pixel = 31 arc s; $1^\circ = 116 \text{ pixels} = 3.15 \times 10^6 \text{ km}$ projected. West is up and north to the left.



metrical around p.a. = 60° , with sharp edges in this direction at 15 and 30 arc s from CC. Coma diameter 5.0 arc min. The WFCC (07:01–09:48 UT) revealed a streamer (p.a. = 1.2° , $d = 252$) pointing almost radially from the coma. On this and the following days, all streamers seen on WFCC frames were on the south side of the main CO^+ tail. Bifurcation of the tail was less evident and possibly located at (3.2, 264). There was a disconnection event (DE) at $d = 9.3$ with several minor condensations just west of the cut. Their outward motion, as measured from the angular displacement during 50 min, was $200 \pm 40 \text{ km s}^{-1}$ in the anti-solar direction.

7 March. CC very strong (an outburst must have occurred during the previous 24 h) and somewhat elongated ($10 \times 13 \text{ arc s}$) towards p.a. = 110° . Jets were present at p.a. = 30° and 120° . Relatively sharp edges were evident at 15 and 40 arc s north-east of CC. The coma diameter was 3.5 arc min (Fig. 2). WFCC (07:30–09:51 UT) observed a main tail that was sharply defined on the north side and more diffuse on the south side. There was a condensation at (3.3, 258) where the tail changed direction to p.a. = 267° . There was evidence of two tail streamers, within 2° from the nucleus. A third, more diffuse streamer left the tail near the condensation mentioned above, at p.a. = 246° —thus it

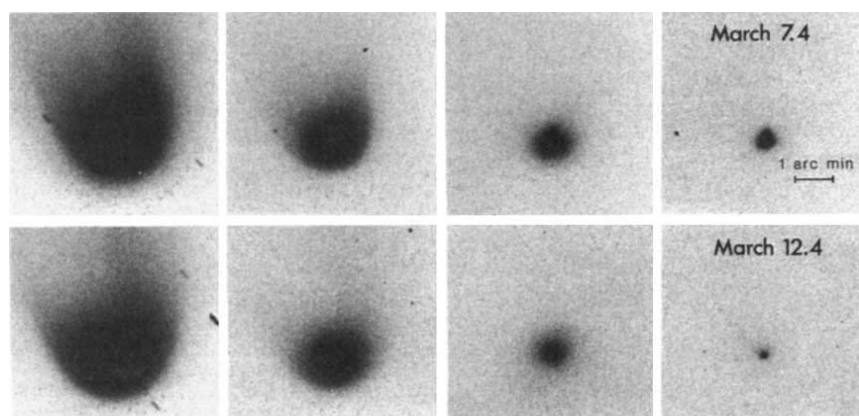


Fig. 2 GPO red (dust) images of near-nucleus region of comet Halley in an active (7.4 March) and a quiescent (12.4 March) phase. 1 arc min = 49,300 km (7.4 March) and 44,100 km (12.4 March) projected. The exposure times are 10 min, 3 min, 1 min and 20 s (left to right) West is up and north to the right.

did not emanate from the region of the coma, but from a point farther west.

8 March. CC was fainter than on 7 March, and round (diameter 3 arc s). Two jets were visible at p.a. = 20 and 60. There was a sharp edge at 25 arc s north-east of CC, where two overlapping parabolas, corresponding to the jets, crossed over. Coma diameter 4.2 arc min. The 30-min blue Schmidt plate revealed a relatively narrow, main ion tail at p.a. = 260, with many undulations. There were at least 10 streamers on the south side that were 0.5–3° long; these were not emanating from the coma but from farther up the ion tail. There were at least seven broad dust tails (synchroes) to $d \geq 3^\circ$ in the p.a. interval 270–330. WFCC (07:28–09:36 UT) observed condensation (DE?) at (5.1,258) whose south-east side was sharply defined. There were 3–4 streamers; the one nearest the main ion tail emanated from $\sim 0.25^\circ$ west of the nucleus.

9 March. CC was round and sharp (diameter 4 arc s), and stronger than on 8 March—almost no material was visible around it on a 20-s exposure. There was a broad fan at p.a. 330–30 on a 60-s exposure with little material south of CC. Coma diameter 5.0 arc min. Schmidt: far fewer streamers than on 8 March; 20-arc-min broad ion tail with rather chaotic structure. Condensation at (1.0,265). WFCC (07:22–09:35 UT): undulating main tail with two streamers showing maximum intensity 1.4° from the nucleus. Condensation slightly off to the north side at (0.94,266), probably representing an early phase of the 10 March DE. The separation from the main tail could be followed from frame to frame.

10 March. CC diffuse and round (diameter 4 arc s) with broad fan in p.a. interval 350–150; strongest at p.a. ~ 100 . A strong streamer towards p.a. = 180 that curved towards the west. The Schmidt plate showed a spectacular elephant's trunk DE at $d = 2.5$ (Fig. 3). WFCC (07:14–09:36 UT): extreme was situated at (2.55,269). Comparison of several frames gave an outward motion of $70 \pm 20 \text{ km s}^{-1}$ in the anti-solar direction (that is, lower than that of the more distant DE on 6 March). This may indicate an acceleration; a similar effect has been mentioned by Jockers⁵. The visible extent of the CO^+ tail was $>17^\circ$ (or $5 \times 10^7 \text{ km}$ projected).

11 March. CC fainter and round (diameter 2 arc s). There was a narrow jet at p.a. = 70 and a broader, fan-shaped jet at 90–120. Diffuse parabola with its tip ~ 40 arc s east of CC. Coma diameter 3.5 arc min. The Schmidt plate shows three narrow ion tails at p.a. = 260, 275 and 280. WFCC (07:12–09:41 UT): nearest point of DE now at (4.8,266).

12 March. CC as on 9 March, that is, round (diameter 3 arc s). Uniform distribution of material, diffuse parabola with little structure visible. Coma diameter 4.0 arc min (Fig. 2). Five major ion tails visible on Schmidt plate; dust tails towards the north-west significantly less intensive than before. Wave-structure in the ion tail towards p.a. = 260. WFCC (07:02–08:39 UT): remains of DE faintly visible. A streamer emanated directly from the coma, reaching (6.0,258).

13 March. CC somewhat stronger than on 12 March (diameter 4 arc s). Much activity in the p.a. 330–120 sector. A main jet emerged at p.a. = 70 and curved towards the south within 15 arc s of the CC. Rather sharp edge 20 arc s north-east of CC. Coma diameter 4.0 arc min. On the Schmidt plate there was a sharp kink at $d = 1.1^\circ$; from here the tail widened. WFCC (06:52–09:31 UT): kink evident at (1.1,258). The main tail and streamers formed a fan system.

14 March. CC again stronger and slightly elongated at p.a. = 100 (diameter 5 arc s). Jets at p.a. = 30 and 110. Edges at 25 and 40 arc s east of CC. Coma diameter 3.0 arc min. The Schmidt plate had a major kink at $d = 2.0$, from which point the ion tail

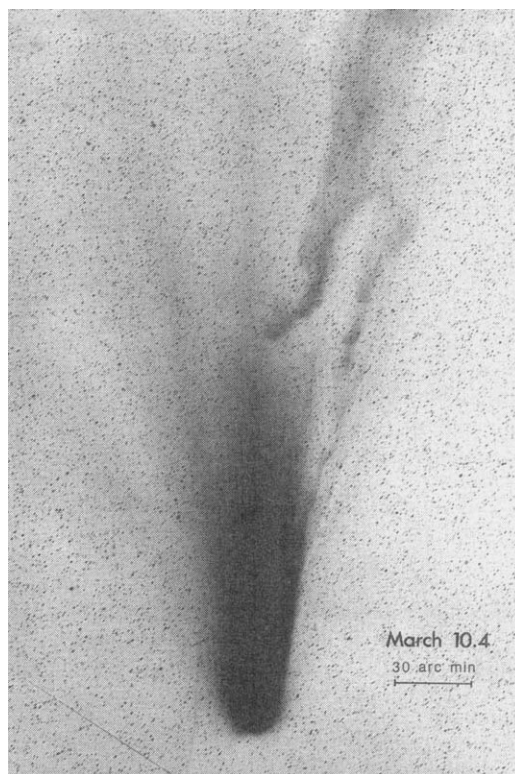


Fig. 3 A 30-min blue (IIa-O+GG385) exposure taken with the ESO 1-m Schmidt telescope on 10.4 March, showing a spectacular disconnection event in the ion tail. 30 arc min = $1.39 \times 10^6 \text{ km}$ projected. West is up and north to the left.

widened. WFCC (06:45–09:31 UT): main tail rather narrow with several kinks and condensations in the interval $d = 2.0$ –4.3 at p.a. = 262; farther out the tail widened significantly. A streamer could be followed from (1.0,257) to (2.1,247).

In summary, during the period 5–14 March 1986, comet Halley experienced important day-to-day changes. The nucleus was relatively quiescent at the time of closest approach of Vega 1 (6.3 March) and Sakigake (11.2 March). There was a major outburst around 7.0 March, which resulted in an increased amount of dust in the inner coma, persisting until closest approach of Suisei (8.5 March) and Vega 2 (9.3 March). At the time of closest approach of Giotto (14.0 March), the nucleus was moderately active and dust jets could be seen in the north-east sector, extending from 10,000 to 20,000 km. The outer dust tail was slowly fading, although several long (2–3°) broad sub-tails persisted in the north-west sector. The ion tail underwent a spectacular disconnection event, starting at ~ 9.4 March, which could be followed until 12.4 March as it moved outwards (in general agreement with Simon's prediction⁶). A less important DE was seen in the outer tail on 6.4 March.

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First journey to a comet

The several space probes passing by comet Halley in March this year have yielded a rich harvest of data in a short time. But many puzzles about this and other comets remain.

THE great journey to comet Halley has been one of the memorable occasions of 1986, and will remain so for many years to come. The data on the preceding pages are striking proof of what has already been accomplished, but there is much more to come. For months and even years, members of the teams that have contributed to this symposium will be working over the now collective data, arriving at conclusions that will no doubt be more measured and even, perhaps, different in some respects. Yet there is a sense, even in science, when the journalistic principle applies that first impressions have a validity of their own.

On this occasion, the first impression derived from the five space probes designed specifically to make observations of the comet is most striking for its uniformity. (An article in next week's issue will explain how the data now published are complemented by observations from a number of US spacecraft adventitiously within range of the comet.) Instruments designed in a dozen different countries and launched by three different space agencies have indeed observed the same remarkable object. This is a striking proof of the care with which the several expeditions to Halley were planned, and thus a pointer to the fruitfulness of the international collaboration over many years which contributed hugely to the success of the several enterprises.

One telling illustration of that was the polyglot atmosphere at the ground stations at Moscow and Darmstadt during the encounters of the Soviet spacecraft, Vegas 1 and 2, and then of Giotto, the European Space Agency's even more sophisticated vehicle. Investigators from different laboratories sat over their recorders crammed together in open spaces that would be described as open-plan if there had been time and space for planning. A glance at the acknowledgements that the various authors have made to others is a sign of how generous other instrument-builders, unable to fly their own constructions, have been with advice and help. And it will similarly be clear that the space agencies, for these purposes the hosts, were concerned above all to see the best possible instruments flown on their spacecraft, irrespective of their national origins.

The Soviet Union's two Vega projects deserve particular acclaim in this respect. The driving force behind this openness was (and is) Academician R.Z. Sagdeev,

the director of the Space Research Institute in Moscow, although it is too easily forgotten that the Soviet space programme has traditionally provided hospitality for other people's instruments (notably French) if on a smaller scale than in the United States. Sagdeev's success in making the Vega projects as thoroughly international as they were is a proof of how a successful and energetic scientist can overcome the usual obstacles to wider collaboration, which stem from bureaucracy rather than malevolence. Everybody's hope is that the collaboration over Halley will lead to even better things, through the mechanism of the Inter-Agency Group which brings together the US National Aeronautics and Space Administration as well as the Soviets, the Japanese and the European Space Agency, probably in a study of solar/terrestrial relationships.

It is also important that the excitement of the Halley encounters should not be forgotten. Because the comet travels in its orbit in the opposite direction to the Earth (and because rocket launchers are still so puny), the close encounters were exceedingly brief — ten minutes or so on either side of the closest approach. The articles in this symposium do not adequately reflect the anxiety with which investigators whose instruments would yield worthwhile data only during that brief interval waited to know whether an accident would destroy several years of work.

The way in which the encounters of the two Soviet spacecraft were used to correct the orbit of the Giotto spacecraft is a further proof of the durability of the collaboration between the different agencies. The "Pathfinder" project (see p.318) may seem in retrospect to have been the only sensible approach to the practical need to adjust the orbit of Giotto to bring that probe within a few hundred kilometres of the target, but it entailed the collaboration of radiotelescopes across the world together with the careful preplanned use of data from the Soviet probes. In the event, Giotto passed by at 600 km, within 100 km of the intended distance and a striking illustration of how the uncertainties in the comet's orbit have been diminished by the Pathfinder project. The uncertainty of the comet's semimajor axis has been reduced from 1,500 km by a factor of about 30, making Halley's orbit the best described of all comets.

Has the whole enterprise been worth-

while? What stands out from this symposium of papers is the surprising complexity of the environment of comet Halley. At the time of the encounters in early March, the comet was already further from the Sun than the innermost planet Mercury, but the space around it for tens of thousands of kilometres was found to be filled (by the standards of the interplanetary vacuum) with gas and dust blown off the comet. Can the influence of the Sun, even on an object cemented together by mere ice, be that powerful?

So far, there is nothing that sharply contradicts the Whipple view of how comets are made, from particles of dust held together by ice. Perhaps the prevalence of carbon dioxide in the gases near the comet shows that there is CO₂-ice as well as water-ice, but that is not in itself a surprise. When more is known of the constitution of the dust, which will come from more careful analysis of the data from the Vega and Giotto probes, it will be time enough for those who believe that comets carry the raw materials of living things, and perhaps even life itself, to throw their hats in the air.

The fact the visible surface of the nucleus of Halley's comet has been found to be relatively cool (300 K) and black (absorbing visible light) is a surprise for what it shows about the mechanism of the evaporation of material from the surface of this comet. Solar radiation evaporates the volatile material which in turn, on the standard picture, carries away the dust as well; that picture is confirmed by what the probes have found about the dust coma, which forms a parabolic zone around the nucleus. But it now seems clear that the solar erosion of the comet's surface is not a uniform process; some parts of the surface become coated with a kind of thermal blanket, while others produce the jets of gas and dust that were such a striking feature of the encounters.

So what happens next? Other opportunities for cometary encounters will recur in the years ahead, but those with instruments on this year's probes have data enough to keep them occupied for the time being. Whether Halley is typical of comets in general is an open question, but now ground-based observers will know more certainly what to look for. Meanwhile, this visit to Halley's comet remains the first close and exciting encounter with primordial material.

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